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Assortative matching with network spillovers.¹

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Abstract

This paper investigates endogenous network formation by heterogeneous agents. The agents' types determine the value of linking and we incorporate spillovers as utility from indirect connections. We provide sufficient conditions for a class of networks with sorting to be stable for low to moderate spillovers; with only two types these networks are the unique pairwise stable ones. We also show that this sorting is suboptimal for moderate to high spillovers despite otherwise obeying the conditions for sorting in Becker (1973). This shows that in our sorted networks a tension between stability and efficiency is present. We analyze a policy tool to mitigate suboptimal sorting.

Keywords: network formation, under-connectivity, assortative matching, network externalities, one-sided matching.

JEL classification: C71; C78; D61; D62; D85.

1. Introduction

Social relations and their network structures are fundamental in almost all aspects of our lives: which jobs we get, how we perceive the world, the decisions we make, etc. (Jackson, 2019). A ubiquitous finding in studies of social relations is the tendency to form more ties with people similar to one-self, i.e. the pattern known

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as *sorting* or homophily, see the meta-study McPherson et al. (2001). Pioneered by Becker (1973), economic research has contributed to the understanding of sorting by providing mathematically sufficient conditions for sorting in marriage- and labor markets to be stable and optimal. The essential condition for sorting is *supermodularity*. This condition entails complementarity in type is such that similar types gain higher value from linking than dissimilar ones. Previous research has not analyzed what implications supermodularity has for assortative matching in the context of networks, either with or without utility from indirect connections.

We extend assortative matching to the context of networks. We demonstrate fundamental properties for a class of networks which we label as having *sorted connectivity*. We require these networks to satisfy the following conditions: *perfect sorting* such that all agents link only with agents of the same type; *type-connectivity* whereby any two agents of the same type are connected; and, *no-link surplus* whereby all available links are used. Intuitively, these networks maximize utility both at the individual and aggregate levels, conditional on perfect sorting. We show that networks with sorted connectivity exist when the number of agents for each type exceeds the number of links allowed per agent and a regularity condition holds, see Proposition 3.

We provide a novel, parsimonious framework which unites the frameworks of complementarity between heterogeneous agents (Becker, 1973) and utility from indirect connections to friends of friends (Jackson and Wolinsky, 1996). In our setup every agent has, at most, a fixed number of links, which reflects limited amounts of time and effort.³ We investigate stability of networks in the following sense: no two agents can form and/or delete links in the network to improve their joint payoff (we allow for transfers of utility). Our central result is that if Becker’s condition for supermodularity holds and spillovers (i.e magnitude of utility from indirect connections) are low to moderate, then networks with sorted connectivity are stable; with only two types of agents it further holds that every stable network has sorted connectivity. See details in Theorem 1.

We also investigate the efficiency for networks with sorted connectivity. For moderate to high spillovers and supermodularity we show that networks with sorted connectivity are inefficient. Therefore, we may refer to inefficient sorted networks as ‘under-connected’ as they have too little connectivity across types relative to the efficient networks. In the situation where there are only two types of agents, and

³A limited number of partners is consistent with empirical research: Ugander et al. (2011) show that the average number of social ties for the entire Facebook network is a few hundred, and likewise Miritello et al. (2013) show the number of phone calls for millions of people is also limited.

supermodularity holds, we strengthen the results: for low spillovers, networks with sorted connectivity are efficient – otherwise, networks with connectivity across types are efficient. Note that among these results, the latter is about global efficiency whereas the former is about comparative (relative) efficiency, see Theorem 2 for details.

The complementarity captured by supermodularity resembles situations where more similarity in matches increases the joint utility. In these situations heterogeneity in type may refer to productive and non-productive capabilities as well as other characteristics with synergy between types. Natural examples include geography or language, as suggested by Church and King (1993). Matching contrary to these characteristics may lead to increased transaction costs or miscommunication and, therefore, to lower aggregate productivity. Another example is combined effects in skills – it could be that matching workers or students with similar skills results in higher joint utility, e.g. as in the classic O-ring model of Kremer (1993). A property of this complementarity is exogeneity; synergy depends only on agents’ pre-defined types, not other parts of the matching/network. We note there are other kinds of homophily/sorting on exogenous characteristics, e.g. eye-color, height. However, these kinds of homophily are often based directly on mutual preference for similarity and do not require conditions on the joint utility. This difference often discussed as transferable versus non-transferable utility, where this paper uses the former framework.

Our results show that Becker’s supermodularity condition is no longer sufficient for sorting to be either stable or efficient. This comes from the fact that agents face a trade-off between two sources of utility: on the one hand, complementarity implies that increased sorting leads to higher direct utility as links between similar agents are more valuable; on the other hand, positive spillovers entail that more sorting can lead to a loss of utility from indirect connections. Therefore, instability and inefficiency of sorting stems from the utility of indirect connections dominating complementarity, which imply that the stable networks are under-connected. However, when combined, our results show that if there are moderate spillovers and supermodularity, then networks with sorted connectivity are stable but inefficient. The reason is that the underlying thresholds governing the two properties are not identical. The intuition behind this incompatibility of stability and efficiency is that two agents forming and removing links will internalize the direct utility from sorting, but they do not internalize the utility from indirect connections for third party agents. We show by visual inspection that the scope for incompatibility (i.e. the region of ‘moderate’ spillovers) widens as the number of agents grows and strength of complementarity increases. We demonstrate in Proposition 4 how to enact policies that curb exces-

78 sive sorting by leveraging contracts that make payoffs conditional on links. These
79 new insights can help policymakers within organizations to design better internal
80 networks by overcoming under-connectivity, e.g. between individuals within schools,
81 corporations or organizations.

82 The policy implications are easy to see in a stylized example. Suppose there are
83 two islands with costly transportation from one to the other. If spillovers are moder-
84 ate in the sense of our model, then the network is under-connected – no inhabitants
85 of either island want to establish connections with inhabitants of the other island as
86 their individual payoff is too small. Nevertheless, by paying agents to connect, every-
87 one could be better off. That is, policies that foster connectivity across the islands
88 can increase the efficiency of the underlying network. With more islands that are all
89 disconnected, the problem can compound and thus the scope for policies increases.
90 Although unrealistic, the results should translate to situations with high levels of ho-
91 mophily combined with strong complementarity and/or many agents. For instance,
92 new empirical work has already shown that a few connections between otherwise
93 connected sub-communities in online social media can foster diffusion of information
94 that otherwise would be unlikely (Park et al., 2018). Our model also helps us to
95 understand the potential consequences of forming organizations that consist of dis-
96 joint parts, e.g. school classes, company divisions. If the organizational parts are not
97 encouraged to interact across affiliated parts, it may lead to no interaction (which is
98 suboptimal), as the disjoint structure provides an implicit complementarity among
99 members from the same part of the organization.

100 This paper also makes a number of additional contributions towards the under-
101 standing of assortative matching. We establish that supermodularity is sufficient for
102 stable networks to contain a general pattern of sorting by type without utility from
103 indirect connections, see Proposition 1. We also show that if the agent population
104 is very large, then sorting is the unique strongly stable outcome (i.e. the core),
105 when Becker’s complementarity condition holds and spillovers are not too high, see
106 Proposition 5.⁴

107 *Literature.* In what follows we review relevant literature and discuss our results in
108 the context of the most related work. A seminal mathematical work on sorting and
109 segregation is Schelling (1969, 1971). Although related, the modeling differences
110 between Schelling’s spatial model and networks (or matchings) are stark; networks
111 are more flexible and allow for connections between any individuals and utility from
112 indirect connections. Two-sided matching captures agents from two distinct sides

⁴The level of spillovers satisfies asymptotic independence in social connections.

113 who match, e.g. in labor and dating markets. The inaugural study on sorting is
114 Becker (1973), which has since been extended to a search setting with match frictions,
115 see Shimer and Smith (2000) and a recent review in Chade et al. (2017). Most of
116 the earlier work on sorting investigates two-sided matching but we use a one-sided
117 matching model. The research on one-sided assortative matching has been limited to
118 formation of partnerships and clubs, which correspond respectively to one-to-one and
119 many-to-many matchings (Farrell and Scotchmer, 1988; Kremer, 1993; Durlauf and
120 Seshadri, 2003; Legros and Newman, 2002; Pycia, 2012; Baccara and Yarovitz, 2013;
121 Xing, 2016).⁵ All the research on one-sided assortative matching finds conditions
122 for sorting which correspond to type complementarity in Becker (1973). Yet, none
123 of the above papers allows for general linking beyond partnerships and clubs, or
124 considers network spillovers. We relax both of these assumptions. We have carefully
125 chosen our framework to use the fundamental concepts from the earlier literature, i.e.
126 supermodularity, a finite capacity for forming links, and pairwise link formation. Our
127 main contribution to the literature on assortative matching is to show which extra
128 conditions in combination with supermodularity lead to stability and efficiency in
129 networks with utility from indirect connections. Another key contribution is that we
130 show potential incompatibility between stability and efficiency and that policies that
131 create incentives to link can fix the issue. We also extend the framework of assortative
132 matching without externalities to a one-sided setting with many partners but without
133 restrictions on link structure (i.e. limited to clubs): Proposition 1 establishes that
134 sorting is stable using a novel measure of sorting which is tractable in equilibrium.

135 The only paper that investigates sorting in networks with externalities is de Martí
136 and Zenou (2017); they also model type complementarity and positive spillovers.⁶
137 Their results show the existence of sorted networks that are stable yet inefficient
138 due to the lack of linking across types.⁷ Although this model is similar to ours,
139 there are crucial differences that motivate our analysis. The essential difference
140 is that we use exogenous complementarity which is independent of the network,
141 while de Martí and Zenou (2017) use endogenous complementarity. de Martí and
142 Zenou (2017) specifically assume that complementarity is strongest when the level of
143 sorting is high, while there is no complementarity when there is negative sorting (i.e.

⁵Buchanan (1965) defines clubs as groups where one's utility depends on all other members. This means that clubs are networks with the implicit assumption that any agents of the same group are all linked. In the networks literature, such groups are known as cliques.

⁶Note that this paper was developed independently and without awareness of de Martí and Zenou (2017).

⁷See Propositions 1.ii, 4.iii in de Martí and Zenou (2017) for results on stable sorting; their Proposition 6 contains results on inefficiency.

144 tendency to link with dissimilar types). This different assumption makes our results
 145 considerably stronger than de Martí and Zenou (2017) when there are two types: we
 146 establish that sorting constitutes the *unique* set of stable networks; we show there
 147 exists a *globally* efficient network that is sorted but has connectivity between groups
 148 and we demonstrate that this network is *implementable* through a simple policy, see
 149 Proposition 4. In addition, our results also apply more generally as they are neither
 150 limited to only five agents of each type, nor to sub-structures of within-type networks
 151 being either stars or cliques, nor to only two types.

152 The essential difference between how we model complementarity here and how
 153 de Martí and Zenou (2017) model it also implies that we interpret our results dif-
 154 ferently. First, our results are relevant in cases when we do *not* expect endogenous
 155 complementarity (see example above). Second, the modeling of complementarity
 156 also entails that the source of inefficiency is different. In our setup suboptimality
 157 stems from misaligned incentives which entail there is a general incompatibility of
 158 efficiency and stability of as in Jackson and Wolinsky (1996). Thus, as sorting is the
 159 unique stable outcome, no one wants to volunteer to build the bridge between com-
 160 munities which increases overall welfare unless there is an outside readjustment of
 161 the incentives, e.g. by policy as we explore or by allowing different contracts (Bloch
 162 and Jackson, 2007). On the contrary, in de Martí and Zenou (2017) the network
 163 with two connected communities, is both efficient and stable. Thus, suboptimality
 164 is not due to incompatibility of efficiency and stability, but rather that agents ended
 165 up in one of the pairwise stable networks characterized by low welfare.⁸

166 There is a vast literature on optimal networks under externalities. The field
 167 has a long tradition and begins with the general formulation under the quadratic
 168 assignment problem (Koopmans and Beckmann, 1957). The field of matching and
 169 networks under externalities was revolutionized by Jackson and Wolinsky (1996)
 170 who demonstrate that there is an incompatibility in networks between stability and
 171 efficiency; Bloch and Jackson (2007) extend these results to show that the tension is
 172 preserved when allowing for more coordination and more flexible transfers between
 173 agents. Although Jackson and Wolinsky (1996) as well as Bloch and Jackson (2007)
 174 show that the incompatibility between stability and efficiency holds generally, they
 175 provide very little in terms of what structure inefficient networks can have. Our

⁸The results in de Martí and Zenou (2017) do not rule out that there can exist stable networks (e.g. some amount of connectivity between groups) that are more efficient than a sorted network. This follows as de Martí and Zenou (2017) have multiplicity in equilibria and they only establish relative inefficiency between two networks (complete network and perfectly sorted network of cliques).

176 contribution is to provide explicit structure to the incompatibility in the context of
177 sorting. This extension may seem small but it has important implications - sorting is
178 a fundamental pattern in empirical networks (McPherson et al., 2001) and therefore
179 we show that the incompatibility may hold widely.

180 The most relevant research on exogenous complementarity in networks is John-
181 son and Gilles (2000); Jackson and Rogers (2005); Galeotti et al. (2006); the first
182 assumes agents all have a unique type with linking costs proportional to their dis-
183 tance, while the two latter use an islands type of model (where agents have same
184 type). Johnson and Gilles (2000) shows existence of a pairwise stable equilibrium
185 with local connectivity between adjacent types, possibly with local cliques where all
186 agents within a given range are connected. Jackson and Rogers (2005) shows that
187 clustering and short paths are robust features among both pairwise stable networks
188 and efficient networks with full linkage among same type. Galeotti et al. (2006)
189 investigate minimally connected networks in a setup with one-sided link formation.⁹

190 There are other strands of literature on homophily in network formation e.g.
191 Currarini et al. (2009, 2010) and Bramoullé et al. (2012). Their approach, however,
192 is different: we use a one period model with strategic link formation, while they rely
193 on matching sequences that are dynamic and stochastic. Currarini et al. (2009, 2010)
194 investigate how differences in community sizes play a role in explaining empirical
195 phenomena, including homophily. Bramoullé et al. (2012) investigate the conditions
196 for long run integration of a network. Other literature has investigated the role of
197 homophily in a model combining referral networks and a labor market (Montgomery,
198 1991; Galenianos, 2018).

199 *Paper organization.* The paper proceeds as follows: Section 2 introduces the model;
200 Section 3 investigates sorting under no externalities; Section 4 analyzes the setting
201 with externalities, focusing on sorting and its potential suboptimality, and; Section
202 5 concludes with a discussion of assumptions. All proofs are found in Appendix
203 Appendix A.

204 2. Model

205 Let $N = \{1, \dots, n\}$ constitute a set of agents. Each agent $i \in N$ is endowed with a
206 fixed measure of *type*, $x_i \in X$, where $X \subset \mathbb{R}$ is the set of (realized) types for agents
207 in N . Let $\bar{x} = \max X$ and $\underline{x} = \min X$. Define the vector of types $\mathcal{X} = (x_1, x_2, \dots, x_n)$.

⁹Note that one-sided link formation is based on the setup of Bala and Goyal (2000) which only requires the weaker equilibrium concept, Nash stability, as links do not need mutual acceptance.

208 Let the agents' type be sorted in descending order according to their label such that
 209 $x_l \geq x_{l+1}$ for $l = 1, \dots, n - 1$.

210 *Linking and networks.* Two agents $i, j \in N$ may *link* if they both accept it. Any of
 211 the two agents who link may break the link without mutual consent. A link between i
 212 and j is denoted $ij \in \mu$, where the set μ consists of links and is called a *network*. The
 213 set of all networks is denoted $M = \{\mu \mid \mu \subseteq \mu^c\}$, where μ^c is the *complete* network in
 214 which all agents are linked.

215 A *coalition* of agents, t , is a subset of agents (i.e. $t \subseteq N$) such that $t \in T$, where
 216 T is the power set of N excluding the empty set. For a given group, t , define $\mathcal{X}(t)$
 217 as the vector of types in descending order over each of the agents in t . A *coalitional*
 218 *move* is a set of actions implemented by a coalition that moves the network from one
 219 state to another. A move from μ to $\tilde{\mu}$ is *feasible* for coalition t if added links, $\tilde{\mu} \setminus \mu$,
 220 are only formed between members of coalition t and deleted links, $\mu \setminus \tilde{\mu}$, only contain
 221 members of coalition t .

222 *Network measures.* The *neighborhood*, ν , is the set of agents who an agent links to:
 223 $\nu_i(\mu) = \{j \in N : ij \in \mu\}$. The number of neighbors is called *degree* and denoted
 224 $k_i(\cdot)$ for i . A *path* is a subset of links $\{i_1i_2, i_2i_3, \dots, i_{l-1}i_l\} \subseteq \mu$ where no agent is
 225 reached more than once; the *length* of a path is the number of links in its set. The
 226 *distance* between two agents, i, j , in a network is the length of the shortest path
 227 between them - this is denoted $p_{ij} : M \rightarrow \mathbb{N}_0$; when no path exists then the distance
 228 is infinite.

229 *Utility.* The utility accruing to agent i is denoted u_i . An agent's utility equals
 230 benefits less costs, expressed mathematically as $u_i = b_i - c_i$. The aggregate utility
 231 is denoted $U(\cdot)$. We model costs of linking indirectly through an opportunity cost
 232 of linking. We do this through a (*degree*) *quota* on links, κ , which is the maximum
 233 number of links for any agent, i.e. for $i \in N$, it holds $k_i(\cdot) \leq \kappa$. We say there
 234 is *no linking surplus* when all agents have a degree equal to the degree quota, i.e.
 235 $\forall i \in N : k_i = \kappa$. The benefit to agent i is a weighted sum consisting of two elements;
 236 network and individual value:

$$b_i(\mu) = \sum_{j \neq i} w_{ij}(\mu) \cdot z_{ij}. \quad (1)$$

237 The network factor $w_{ij}(\mu)$ is a function of network distance. The individual link
 238 value is z_{ij} , which measures the personal value to i of linking to j - the value is a
 239 function of the two partners' types $z_{ij} = z(x_i, x_j)$. The function z is assumed twice

240 differentiable as well as taking positive and bounded values.¹⁰ Let the *total link value*
 241 be defined as the value of linking for the pair, i.e. $Z_{ij} = z_{ij} + z_{ji}$.

242 In order to derive results, a restriction of payoffs is necessary. The essential
 243 feature of the total link value for sorting is complementarity in type:¹¹

244 **Definition 1.** *The link value has **supermodularity** if $\frac{\partial^2}{\partial x \partial y} Z(x, y) > 0$. This entails:*

$$Z(x, \tilde{x}) + Z(y, \tilde{y}) > Z(x, y) + Z(\tilde{x}, \tilde{y}), \quad x > \tilde{y}, \tilde{x} > y. \quad (2)$$

245 The network components are further restricted in the analysis under externalities
 246 in Section 4.

247 *The game framework.* This paper explores a static setting of one period. Agents'
 248 information about the payoffs of other agents is complete. Together the players,
 249 action, utility and information constitute a game.

250 We assume that any pair of agents can transfer ‘utility’ between them. Let a
 251 *net-transfer* from agent j to agent i be denoted as $\tau_{ij} \in \mathbb{R}$ such that $\tau_{ij} = -\tau_{ji}$,
 252 which implies non-wastefulness of utility. The matrix of net transfers is denoted τ .
 253 Transfers can be exchanged by any pair of agents. We specifically assume that for
 254 any pair of agents there is mutual dependence between transfers and their link, if
 255 they have one. This entails that a transfer cannot be changed unless both agents
 256 agree, otherwise the non-consenting agent can break the link. Conversely, if the link
 257 is broken without mutual consent, then the transfers are set to zero. Although this
 258 seems similar to Bloch and Jackson (2007), the conditionality here is only between
 259 agents who are linked.

260 *Stability.* We define network stability using coalition moves. A coalition t is *blocking*
 261 a network μ with net-transfers τ if there is a feasible coalition move from network μ
 262 to network $\tilde{\mu}$ with $\tilde{\tau}$ where all members in t have a higher net-payoff after the move.

263 We employ two concepts of stability. The first is *strong stability*: this is satisfied
 264 for a network if there exist transfers such that no coalition (of any size) may have
 265 a feasible move that is profitable for all its members. The second concept, *pairwise*
 266 *(Nash) stability*,¹² is similar but has weaker requirements: it holds when there exist
 267 transfers where it holds that no coalitions of at most two agents may block. A further
 268 discussion of the stability concepts is found in Section 5.

¹⁰The upper bound rules out an infinite number of links in equilibrium.

¹¹Complementarity between type corresponds to cheaper links between same/similar types used in the models of Johnson and Gilles (2000); Jackson and Rogers (2005); Galeotti et al. (2006).

¹²This is also known as bilateral stability, cf. Goyal and Vega-Redondo (2007).

269 Our pairwise definition of stability is stricter than that of Jackson and Wolinsky
 270 (1996). However, the stricter requirement enables substitution of links (simultaneous
 271 deletion and formation), which is a necessary requirement for establishing results in
 272 the matching literature.

273 A noteworthy feature is that strong stability implies pairwise stability; thus any
 274 condition valid for all pairwise stable networks also applies to any strongly stable
 275 network. In addition, without utility from indirect connections (i.e. no spillovers),
 276 every pairwise stable network is also strongly stable, see Lemma 1. Note also that
 277 any strongly stable network requires efficiency (coalition of all agents can implement
 278 any network). We use the efficiency property of strongly stable networks to derive
 279 the structure of these networks in Proposition 5.

280 3. Analysis: no spillovers

281 This brief section analyzes the setting without utility from indirect connections.
 282 We begin with defining our measure of sorting. The concept of sorting that we
 283 employ is a generalization of the sorting when there is a single partner, such as in
 284 Becker's marriage market. The shape of sorting is such that a high type agent has
 285 partners which weakly dominate in type when compared partner-by-partner with the
 286 partners of a lower type agent. Note the comparison is done over the sorted set of
 287 partners type \mathcal{X} . The sorting pattern is mathematically defined as:

288 **Definition 2.** *Sorting in type holds in μ if for all pairs i, j such that $x_i > x_j$ it*
 289 *holds that:*

$$\mathcal{X}(\nu_i(\mu)/\{j\})_l \geq \mathcal{X}(\nu_j(\mu)/\{i\})_{l+l^*}, \quad \forall l \in \{1, \dots, k^*\},$$

290 where $k^* = \min(k_i(\mu), k_j(\mu))$ and $l^* = \max(k_j(\mu) - k_i(\mu), 0)$.

291 Our first result is that sorting in type emerges under the same conditions as in
 292 Becker (1973) when network externalities are absent:

293 **Proposition 1.** *If there is supermodularity and no externalities, then for any pair-*
 294 *wise stable network there is sorting in type.*

295 The proof of this proposition follows by establishing that a pairwise stable net-
 296 work must be strongly stable without externalities; then we use that strongly stable
 297 networks are efficient and show that sorting in type must hold under efficiency.¹³

¹³Note that the current proof relies on comparing partner order of l for i with order $l + l^*$ for j in Definition 2. We conjecture that this can be relaxed to comparison partner of order l of i with order $l + l^*$ of j .

298 4. Analysis: positive spillovers

299 We proceed to a more general context where indirect connections matter for
 300 utility. Whenever we allow for externalities we restrict our attention to two forms of
 301 linking utility.

$$w_{ij}(\mu) = \begin{cases} \delta^{p_{ij}(\mu)-1}, & \text{constant decay,} \\ \mathbf{1}_{=1}(p_{ij}(\mu)) + \delta \cdot \mathbf{1}_{\in[2,\infty)}(p_{ij}(\mu)), & \text{hyperbolic decay,} \end{cases} \quad (3)$$

302 where $\mathbf{1}_{\in(1,\infty)}(l)$ is the Dirac measure/indicator function of whether $1 < l < \infty$.

303 The first and more general setting is where utility from connections decays over
 304 increasing distance at a constant exponential rate. This corresponds to benefits from
 305 linking in the ‘connections-model’ from Jackson and Wolinsky (1996). The other case
 306 is when externalities from indirect connections are discounted equally at any distance
 307 if there is a connection, i.e. a finite path length. This second case is referred to as
 308 hyperbolic decay and entails that there is no decay beyond that from distance one
 309 (linked) to distance two.

310 The introduction of externalities to our framework implies that the pairwise util-
 311 ity no longer depends only on the total link benefits. As a consequence, sorting is not
 312 guaranteed to be either stable or efficient. The intuition for this is straight forward:
 313 externalities entail that the total welfare from sorting is internalized for the pair,
 314 while the total welfare for indirect connections are not internalized. We see this by
 315 inspecting the utility functions. Suppose that \hat{g} is a pairwise deviation such that
 316 agents i, j form a link. Then the pairwise total net utility from deviation can be
 317 expressed as follows under externalities:

$$u_i(\hat{g}) + u_j(\hat{g}) - u_i(g) - u_j(g) = Z_{ij} + \sum_{k \in \{i,j\}, l \notin N \setminus \{i,j\}} z_{kl} \cdot (\delta^{p_{kl}(\hat{g})} - \delta^{p_{kl}(g)}) \quad (4)$$

318 From the analysis in the previous section we found that, in the absence of ex-
 319 ternalities, sorting prevails. In the above equation this incentive to sort is captured
 320 by the component Z_{ij} . Therefore, we see that the total benefits from sorting are
 321 preserved for the pair.

The total benefits to all agents that accrue from agents i, j forming a link are:

$$\begin{aligned} U(\hat{\mu}) - U(\mu) &= u_i(\hat{\mu}) + u_j(\hat{\mu}) - u_i(\mu) - u_j(\mu) + \sum_{l \notin N \setminus \{i,j\}} [u_l(\hat{\mu}) - u_l(\mu)] \\ &= u_i(\hat{\mu}) + u_j(\hat{\mu}) - u_i(\mu) - u_j(\mu) + \sum_{l \notin N \setminus \{i,j\}, l' \in N, l' \neq l} Z_{ll'} \cdot (w_{ll'}(\hat{\mu}) - w_{ll'}(\mu)) \end{aligned} \quad (5)$$

322 Inspection of Equation 5 informs us that the pairwise utility of linking does not
 323 capture the aggregate gains from linking. Moreover, we see that the gains not cap-
 324 tured correspond to the indirect benefits that others receive from the deviation. This
 325 implies that there is a disparity between the pairwise incentives and total welfare:
 326 the pairwise incentives capture the full benefits of sorting but not the full gains from
 327 lower distances between agents.

328 4.1. Finite population

329 We begin with the situation where there are a finite number of agents. Before
 330 starting the analysis of networks under externalities we define some useful concepts.
 331 Naturally, we call networks perfectly sorted when the agent of each type only link
 332 among themselves. A further important distinction is whether the subnetworks for
 333 each type are connected among agents of the same type. Such connectivity is suffi-
 334 cient for agents to reap all the gains of utility from indirect connections when sorting
 335 occurs if there is hyperbolic decay in spillovers. Finally, we want to ensure that there
 336 is no surplus of links as this would imply wastefulness, which is not in the interest
 337 of agents as they always benefit from linking. Combining these concepts we can
 338 introduce our main concept, sorted connectivity of networks:

339 **Definition 3.** *A network has **perfect sorting** if every linked pair of agents have*
 340 *the same type.*

341 **Definition 4.** *A network is **type connected** if every two agents of the same type*
 342 *is connected.*

343 **Definition 5.** *An agent i has **link-surplus** in a given network if i 's number of links*
 344 *is lower than the degree quota.*

345 **Definition 6.** *A network is **sort-connected** if the network (i) is perfectly sorted,*
 346 *(ii) is type connected and (iii) no agents have a link surplus in the network.*

347 We now turn to type self-sufficiency, which requires that there is potential for
 348 each type to perfectly sort and have no link surplus. This concept is important and
 349 plays a critical role for the existence of sort-connected networks.

350 **Definition 7.** *A type of agents $x \in X$ is **self-sufficient** if $n_x > \kappa$.*

351 We briefly investigate the situation when type self-sufficiency does not hold, i.e.
 352 $n_x \leq \kappa$ for one or more types $x \in X$. This is seen from the following statement:

353 **Proposition 2.** *Suppose there is supermodularity and there is not type self-sufficiency:*

- 354 (i) if $n \leq \kappa + 1$ then the complete network is the only pairwise stable network and
 355 the only efficient network;
- 356 (ii) if $n > \kappa + 1$ and there are two types where $n_{\bar{x}} = n_x$, then every network where
 357 every agent has $n_{\bar{x}} - 1$ same-type links, and $\kappa - n_{\bar{x}} + 1$ cross-type links is stable
 358 and efficient.

359 We move on to examining sorted connectivity in networks. We note that the
 360 remainder of this subsection is restricted in two ways. First, by confining our analysis
 361 to the setting where there is self-sufficiency for each type. Second, we exclusively
 362 focus on the case of hyperbolic decay as it provides for more intuitive and more
 363 immediate results without restrictions on the network. As noted earlier, a more
 364 general exposition is found in Supplementary Appendix Appendix B.

365 The aim is to show that sort-connected networks are stable when the strength of
 366 utility from indirect connections is low to moderate. Moreover, when the strength of
 367 utility from indirect connections is moderate to high, the networks are suboptimal
 368 despite fulfilling Becker’s complementarity condition, i.e. supermodularity. We will
 369 see that the suboptimality arises because the network is under-connected relative to
 370 the efficient network.

371 We begin our analysis by presenting an illustration of the situation. We want
 372 to show that for strength of utility from indirect connections below the threshold,
 373 δ^{stab} , any network with sorted connectivity is also pairwise stable. Moreover, we will
 374 show that there exist networks with higher aggregate utility when utility exceeds
 375 another threshold, δ^{opt} . In order to motivate and capture the intuition we provide
 376 simplified results in Example 1. The example is based on hyperbolic decay of network
 377 externalities, however, it can be easily adapted to constant decay.¹⁴ The example is
 378 graphically represented in Figure 1.

379 **Example 1.** *There are six agents; three of high type (1,2,3) and three of low type*
 380 *(4,5,6). Moreover, there is supermodularity, degree quota of two ($\kappa=2$) and hyperbolic*
 381 *decay. Define two networks: a network with sorted connectivity, $\mu = \{12, 13, 23, 45, 46, 56\}$,*
 382 *see Figure 1.A; a sort-connected network with bridges (see Definition 8), which we*
 383 *denote as $\tilde{\mu} = \{12, 23, 34, 45, 56, 61\}$, see Figure 1.C. We show in this example that,*
 384 *for a range of decay-factors, μ is pairwise stable, yet suboptimal. In this setup there*
 385 *is a unique move which is both feasible and payoff relevant.¹⁵ This move consists in*

¹⁴In an old paper version, Bjerre-Nielsen (2015), we compute the example under constant decay of spillovers.

¹⁵Under pairwise stability at most one link can be formed in a single move. As the value of every

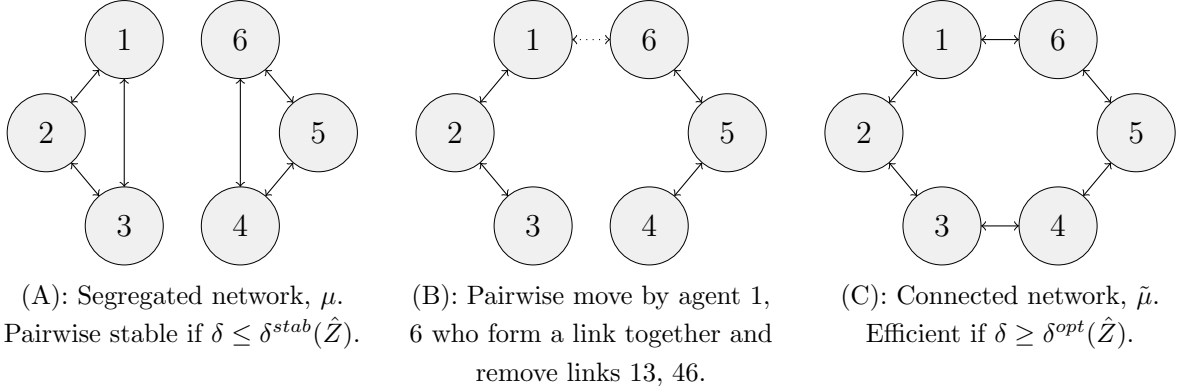


Figure 1: *Sorted network is stable but inefficient.*

The above three networks depict Example 1. The network in (A) is pairwise (Nash) stable for some parameters and the network in (B) is the only kind of feasible deviation. The network in (C) is an efficient network.

386 two agents forming a link across types and both participating agents delete a link.
 387 Such a move could be agents 1,6 forming a link while deleting their respective links
 388 to agents 3 and 4. We denote this network $\hat{\mu} = \mu \cup \{16\} \setminus \{13, 46\}$ and we plot it in
 389 Figure 1.B. Benefits for agents 1 and 6 from network μ and deviating from it are:

$$\begin{aligned}
 u_1(\hat{\mu}) + u_6(\hat{\mu}) &= (1 + \delta) \cdot [z(\bar{x}, \bar{x}) + z(\underline{x}, \underline{x})] + [1 + 2\delta] \cdot [z(\bar{x}, \underline{x}) + z(\underline{x}, \bar{x})], \\
 &= (1 + \delta) \cdot \frac{1}{2} \cdot [Z(\bar{x}, \bar{x}) + Z(\underline{x}, \underline{x})] + [1 + 2\delta] \cdot Z(\bar{x}, \underline{x}), \\
 u_1(\mu) + u_6(\mu) &= 2 \cdot [z(\bar{x}, \bar{x}) + z(\underline{x}, \underline{x})] = Z(\bar{x}, \bar{x}) + Z(\underline{x}, \underline{x}).
 \end{aligned}$$

390 We can express the condition that the deviation to $\hat{\mu}$ is not pairwise profitable as:
 391 $u_1(\mu) + u_6(\mu) > u_1(\hat{\mu}) + u_6(\hat{\mu})$. This condition is sufficient for pairwise stability due
 392 to payoff symmetry in μ and no transfers.

393 We now turn to deriving the condition for segregation to be inefficient. The
 394 aggregate benefits over all agents of the two networks, μ and $\tilde{\mu}$, is expressed below in
 395 the two equations.

$$\begin{aligned}
 U(\tilde{\mu}) &= (2 + \delta) \cdot [Z(\bar{x}, \bar{x}) + Z(\underline{x}, \underline{x})] + [2 + 7\delta] \cdot Z(\bar{x}, \underline{x}), \\
 U(\mu) &= 3 \cdot [Z(\bar{x}, \bar{x}) + Z(\underline{x}, \underline{x})].
 \end{aligned}$$

link is positive it follows that a move consisting only in deletion of a link always leads to a loss. Thus, only coalition moves where new links are formed can be valuable. All links to same type agents are already formed in network μ . Therefore, the only feasible move consists in forming a link to agents of the other type.

Sorting is inefficient when: $U(\mu) < U(\tilde{\mu})$. The two inequalities governing pairwise stability and inefficiency have the following positive solution:

$$\begin{aligned}\delta^{stab}(\hat{Z}) &= \frac{\hat{Z}}{\hat{Z}+1}, & \hat{Z} &= \frac{Z(\bar{x},\bar{x})+Z(x,x)}{2Z(\bar{x},x)} - 1, \\ \delta^{opt}(\hat{Z}) &= \frac{\hat{Z}}{\hat{Z}+\frac{9}{2}},\end{aligned}$$

where δ^{opt} and δ^{stab} are thresholds for, respectively, when network μ becomes inefficient, and unstable when δ increases.

The example above demonstrates that sorting can be inefficient when there are network effects despite there being complementarity in type, i.e. supermodular link values. The inefficiency stems from a novel source - the pairwise formation of links. The intuition is that under pairwise deviation the two agents do not internalize the total value created for the other agents; number of indirect links between a high and a low agent. Note that the above example has a close correspondence to Propositions 1 and 6 from de Martí and Zenou (2017) and that their results also holds only for cliques with very few agents (≤ 5), see literature review.

We proceed with a generalization of the example above which holds for various structures of the subnetworks within types and for multiple types. The aim is to extend the above example to a less restrictive setting for sorted connectivity. Below is our first general result where we establish sufficient and necessary conditions for the existence of networks with sorted connectivity.

Proposition 3 (Existence). *The set of sort-connected networks is non-empty if and only if all of the following conditions hold:*

- i) *there is self-sufficiency for each type;*
- ii) *more than one partner is allowed.*
- iii) *either the degree quota is even or there is an even number of agents of each type;*

The conditions in Proposition 3 are listed in order of importance. The essential condition is self-sufficiency, which ensures that there are enough links for each type to perfectly sort. The second condition of the degree quota exceeding one, is obvious as otherwise the problem would reduce to a simple one-to-one matching problem and type connectivity would not be possible. The final condition requiring either even numbered quota of links or even number of agents for each type is a little subtle. The reason is technical; if both of these conditions are not met then the total demand for links of the same type is uneven when there is no link surplus but each link takes up

a capacity of two and thus must be an even number; the implication is that perfect sorting and no link surplus is incompatible when this even number condition is not met. We discuss the choice of equilibrium concepts in the discussion found in Section 5.

We move on to investigate stability and optimality of the network structure. We now generalize the thresholds from Example 1. These thresholds for stability and optimality hold for any number of types and number of agents for each type. Note that for optimality the value provided below is an upper bound of threshold value.

$$\delta^{stab} = \min_{x, \tilde{x} \in X} \left(\frac{\hat{Z}_{x, \tilde{x}}}{\hat{Z}_{x, \tilde{x}} + \max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x, \tilde{x}}} \right), \quad \hat{z}_{x, \tilde{x}} = \frac{z(x, \tilde{x})}{Z(x, \tilde{x})} \quad (6)$$

$$\bar{\delta}^{opt} = \min_{x, \tilde{x} \in X} \left(\frac{\hat{Z}_{x, \tilde{x}}}{\hat{Z}_{x, \tilde{x}} + \frac{1}{2} n_x n_{\tilde{x}}} \right), \quad \hat{Z}_{x, \tilde{x}} = \frac{Z(x, x) + Z(\tilde{x}, \tilde{x})}{2Z(x, \tilde{x})} - 1 \quad (7)$$

Using the first threshold above we can express our main result on the stability of sort-connected networks. Note that an alternative version of the above theorem under constant decay can be found in Appendix Appendix B in Theorem 3.

Theorem 1 (Stability). *Suppose there is supermodularity, then every sort-connected network is pairwise stable if $\delta \leq \delta^{stab}$; moreover, if there are only two types and sort-connected networks exist, then every pairwise network is also sort-connected.*

We have shown general stability of sort-connected networks. Moreover, when there are only two types, our results from Theorem 1 are substantially stronger. We establish that sorting is the unique pairwise stable outcome for low to moderate levels of externalities (i.e. $\delta < \delta^{stab}$).

We emphasize that Theorem 1 and δ^{stab} have implications for understanding the instability of perfect sorting in networks. For sufficiently high levels of spillover, i.e. $\delta > \delta^{stab}$, it holds that sorted networks are never pairwise stable. The reason is that agents of different types can benefit jointly by mutually forming a link and each breaking a same type link.

One can view Theorem 1 as generalizing not only Example 1 but also Propositions 1.ii and 4.iii from de Martí and Zenou (2017), who require that there are very few agents, two types and all agents of a given type link with one another.

We move on to discussing another main property of sort-connected networks, namely optimality, i.e. whether the network structure is efficient. In order to state our results we introduce a related network which has efficiency properties for moderate to high strength of utility from indirect connections.

454 **Definition 8.** Let a **bridged, sort-connected** network be a sort-connected network
 455 where (i) for at least two types exactly one link is broken, (ii) each agent with a broken
 456 link forms exactly one link to other agents across types who also have a link broken.

457 It is important to understand that in our model moving to a bridged, sort-
 458 connected network require two links to be established across types from a sort-
 459 connected network. This is a technical condition stemming from the fact that re-
 460 ducing the number of links among the same type by one frees up the capacity to
 461 establish a link by two agents; as a consequence it is possible for two links across
 462 types to be established. Using both of these possible links is important for establish-
 463 ing efficiency. It will turn out to also be important in the investigation of policy, see
 464 Proposition 4.

465 **Theorem 2** (Efficiency). Suppose there is supermodularity, then the thresholds for
 466 efficiency and stability satisfy $\bar{\delta}^{opt} < \delta^{stab}$. Any sort-connected network is inefficient
 467 when $\delta < \delta^{opt}$ where it holds that $\delta^{opt} \leq \bar{\delta}^{opt}$. Finally, if there are two types then, sort-
 468 connected network are efficient when $\delta \leq \bar{\delta}^{opt}$, while bridged, sort-connected networks
 469 are efficient for $\delta \geq \bar{\delta}^{opt}$.

470 The above theorem generalizes Example 1 by showing that under-connected net-
 471 works with too little linking across sorted groups of agents occur more generally. It
 472 also extends Proposition 6 from de Martí and Zenou (2017) by removing the restric-
 473 tion to two types and linking between all same type agents as well as doing away
 474 with the limitation of having very few agents. Again, with only two types of agents
 475 the results are considerably stronger. We can show that the threshold for inefficiency
 476 now governs whether it is the sort-connected network or the bridged, sort-connected
 477 network that is efficient.

478 A visualization of the computed thresholds of externalities when there are two
 479 types is found in Figure 2. The thresholds are computed for varying population
 480 size and varying strength of complementarity. These plots can be seen as providing
 481 comparative statics along these two dimensions. The upper part of the figure keeps
 482 the population size fixed while lower ones keep the complementarity strength fixed.
 483 From inspection it is evident that both of the connection thresholds are approxi-
 484 mately linear in log-log scale. This pattern suggests that both of the thresholds fol-
 485 low power-laws in the number of agents and strength of complementarity. Note that
 486 it is also straightforward to mathematically derive these patterns from the threshold
 487 definitions. Note also that it is possible to do a comparative static in the number of
 488 types. For example, if we assume that all same type agents get a certain payoff and
 489 cross type relations get some fraction of that, as in Jackson and Rogers (2005), then

490 increasing the number of islands keeps the gain from pairwise deviation constant,
 491 but the gains in efficiency increase.

492 The remainder of this subsection will sketch a policy intervention that can mit-
 493 igate the problem of suboptimal sorting by improving welfare through encouraging
 494 connection. These interventions can be seen more generally as a design problem,
 495 where the policy maker intervenes to induce a network that produces higher welfare.
 496 The tool that the policy maker employs is providing incentives to agents for forming
 497 specific links. Note that two agents of each type may need to be compensated. This
 498 stems from the fact that when compensating one agent to establish a link across
 499 types the agent to which it has deleted a link has an incentive to form a new link,
 500 which will potentially destabilize the sub-networks for each type. We discuss this
 501 assumption and how it relates to our choice of model in Section 5.

502 Define a *link-contingent contract* as a non-negative transfer, \mathcal{C}_{ij} , paid to i for
 503 linking with another agent j . Denote the vector of link-contingent contract as \mathcal{C} . We
 504 start demonstrating our results on intervention through a continuation of Example 1.

505

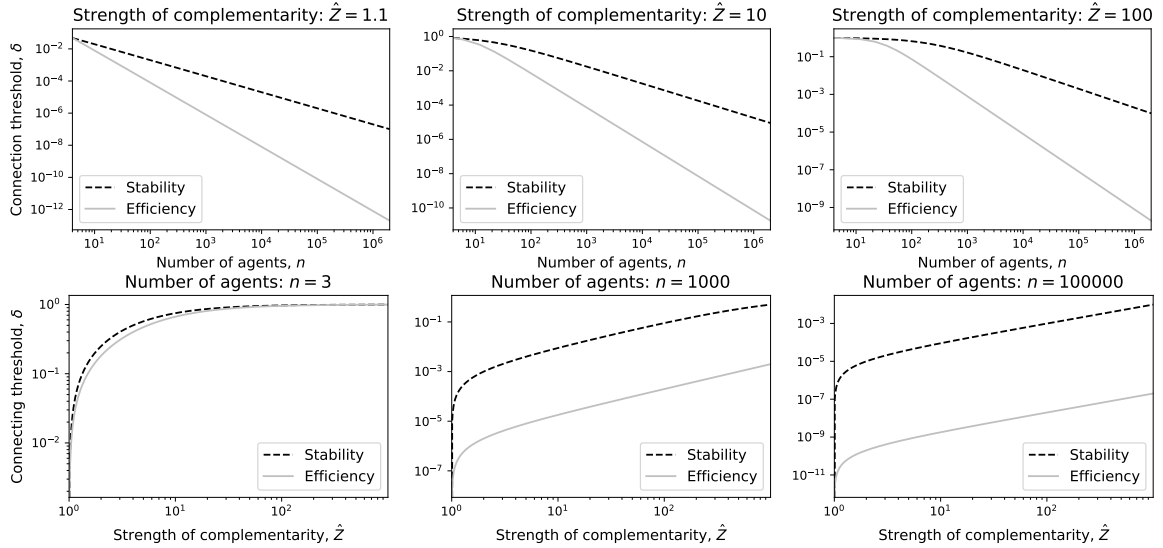


Figure 2: *Thresholds for connecting.*

Visualization of thresholds for connecting from Theorems 1 and 2. The upper part shows varying sizes of populations and fixed strength of complementarity. The lower part has varying strength of complementarity and fixed population sizes. It is assumed that there are two types which have an identical number of agents.

506 **Example 1 (continued)** Let strength of utility from indirect connections satisfy
 507 $\delta < \delta^{stab}$ and assume that there is a policy maker who can issue link-contingent
 508 transfers as follows. We suppose that the policy maker offers conditional transfers
 509 such that the pairwise net-utility for agents 1,6 and agents 3,4 from forming a link
 510 satisfies:

$$C_{ij} + C_{ji} = -[(1 - \delta) \cdot (z(x, x) + z(\tilde{x}, \tilde{x})) + (1 + 2\delta) \cdot z(x, \tilde{x})] + \varepsilon, \quad ij \in 16, 34, \quad \varepsilon > 0$$

511 Agents 1,6 and 3,4 have an incentive to form a link and break their existing links (i.e.
 512 $\{13, 46\}$). This implies that a deviation from the sort-connected network μ to the
 513 bridged, sort-connected network $\tilde{\mu}$ is possible; see the networks depicted in Figure 1.
 514 We round off the example by noting that if $\delta > \delta^{opt}$, then the deviation to the bridged,
 515 sort-connected network raises aggregate utility.

516

517 We now generalize the insight from the continuation of Example 1 into the follow-
 518 ing proposition. This proposition holds for an arbitrary number of agents when there
 519 are two types. We need to define an auxiliary term to describe the interventions:

520 **Definition 9.** Let a network $\tilde{\mu}$ be **implementable** from μ, τ given \mathcal{C} if there exist
 521 a sequence of tuples $(\mu_0, \tau_0), \dots, (\mu_l, \tau_l)$ where $\mu_0 = \mu$, $\mu_l = \tilde{\mu}$, and $\tau_l = \tau$ such that:
 522 for $q = 1, \dots, l$ from μ_{q-1} to μ_q is a feasible pairwise move which increases the pair's
 523 net-utility most given \mathcal{C} , and; $\tilde{\mu}$ is pairwise stable given τ_q and \mathcal{C} .

524 **Proposition 4** (Implementation). Suppose that there are two types, supermodularity
 525 and $\delta < \delta^{stab}$. It follows that a policy maker can implement a bridged, sort-connected
 526 network from any sort-connected network.

527 The above result shows it is possible to have agents deviate to implement the
 528 bridged, sort-connected networks by offering link-contingent contracts. By combining
 529 the proposition with earlier results on inefficiency, it follows directly that:

530 **Corollary 1.** If conditions for Proposition 4 hold and $\delta > \bar{\delta}^{opt}$ it follows that imple-
 531 menting the bridged, sort-connected network will result in higher welfare.

532 The intuition of the corollary is that efficiency can be restored by compensating
 533 certain agents. Recall that in our model conditionality of transfers exist only between
 534 agents who are linked. This lack of conditionality for third parties implies that
 535 agents cannot fully internalize positive spillovers. Therefore, it is not surprising that
 536 efficiency is restored when allowing a third party, i.e. the policy maker, to transfer
 537 utility conditional on certain links as has been shown previously (Bloch and Jackson,
 538 2007). We note that Proposition 4 and Corollary 1 outline a centralized intervention

by a policy maker but it could also have been solved decentrally through conditional transfer by other agents, as in the framework of Bloch and Jackson (2007).

We note that the individual compensation paid to agents for connecting to others may not be equal. In particular, the payment may also depend on the types. This is the case when there is both supermodularity and monotonicity in Z . If these conditions hold, then agents may receive compensation that is increasing with their type.

4.2. Infinite population - constant decay in spillovers

We finalize this section by investigating what pattern of linking is exhibited when the count of agents becomes asymptotically infinite. In this large matching market we examine asymptotic perfect sorting, i.e. when the measured share of links to same-type agents converges to one. We employ the constant decay to measure utility from indirect connections as hyperbolic decay yield infinite payoff for any connected network with infinite number of agents. Note that we also use a stronger equilibrium concept, strong stability, which allows for coordination between coalitions of any size.

Definition 10. Let *asymptotic perfect sorting* hold for a sequence of networks sets, M_n , if for any network, $\mu \in M_n$, where $n \rightarrow \infty$, it holds that $|\{ij \in \mu : x_i = x_j\}|/|\mu| \simeq 1$.

Define *asymptotic independence* as $\delta < (\kappa - 1)^{-1}$. For large matching markets the sufficient conditions for asymptotic perfect sorting to emerge in strongly stable networks are:

Proposition 5. If there is supermodularity, a degree quota and constant decay with asymptotic independence, then there is asymptotic perfect sorting for strongly stable networks.

The result above demonstrates that the availability of many agents for linking induces perfect sorting in strongly stable networks. It demonstrates the same prediction as the conclusion of Becker (1973) for the marriage market model but holds in the presence of externalities with constant decay.

For deriving the result we exploit strong stability which implies that efficiency holds. Therefore, it is sufficient to show that asymptotic efficiency requires asymptotic perfect sorting. Although efficiency is a unique property for strong stability (and does not hold for weaker concepts) it can be argued that strong stability should

571 be seen as a refinement with desirable properties which makes it more likely when it
572 exists.¹⁶

573 We conclude this section by noting that we may interpret the result on sorting
574 for infinite populations differently; there is no loss from sorting when there are many
575 agents.

576 5. Concluding discussion

577 We have extended the assortative matching framework to a setting of networks.
578 We have shown that in a general context that Becker’s condition for sorting is still
579 essential for stability. However, the same condition is insufficient for efficiency (when
580 there is a finite population). The context is where types have enough members to
581 form a community among themselves. We have sketched a policy that can help
582 overcome this issue.

583 We have chosen to model costs implicitly via a degree quota in order to have
584 comparability with the matching literature. We expect, however, that our results
585 should easily translate to the standard connections model of Jackson and Wolinsky
586 (1996). In this other setup we expect that the intuition should transfer when limiting
587 the number of sub-networks within types to be either cliques or stars, as in de Martí
588 and Zenou (2017). One advantage of translating the setup to the linear cost frame-
589 work of the standard networks literature would be that the technical assumption of
590 either even degree or an even number of agents for each type would not be necessary.
591 Under hyperbolic decay one would also get a more natural efficient policy solution
592 requiring only a single agent of each type to bridge the gap between their respective
593 subnetworks.

594 Our analysis is based on other strict assumptions which we now review. We
595 begin by noting that search frictions are important and have received attention in
596 the literature (Chade et al., 2017) but for the sake of tractability we focus on a
597 frictionless model. There are also a number of restrictive assumptions on payoff. The
598 most crucial assumptions are payoff separability and fixed structure of externalities.
599 Further research could explore how results generalize to less restrictive utility from
600 indirect connections captured by the decay parameter, δ . For instance, does there
601 exist a set of criteria that are more general than constant or hyperbolic decay for
602 which our results hold. It is likely that our results are robust to including utility from

¹⁶In some circumstances the existence of contracts where an agent may subsidize or penalize another agent’s link formation with alternative agents may imply strong stability even if contracts were limited to being pairwise specified, cf. Bloch and Jackson (2007).

network measures, e.g. triadic closure/clustering, that are common in the literature within economics on networks. Other critical assumptions are supermodularity and perfect transferability. Nevertheless, as mentioned in the introduction, these two assumptions can be replaced by monotonicity in individual link values and perfect non-transferability, which is also in line with some research on peer effects.¹⁷ Finally, the model relies on some agents being of different types but it should be possible to remove this assumption.¹⁸

Another caveat with our analysis, and stable networks in general, is that these networks may not exist. We have shown some properties of existence under regularity conditions of sort-connected networks, see Propositions 3 and 1. However, beyond sort-connected networks we do not offer much in the case of externalities. The gross substitutes conditions from Kelso and Crawford (1982), which ensure existence of stable matchings in related settings, are not satisfied in our setting with externalities.¹⁹ Nevertheless, by changing the equilibrium concept we expect that some of the lack of existence could be solved. One approach is using farsighted stability, as in Chwe (1994); Dutta et al. (2005); Herings et al. (2009). Another approach is using some approximative equilibrium concept e.g. cost of stability (the necessary payments to induce stability) from Bachrach et al. (2009).

Appendix A. Proofs

Lemma 1. *In the absence of network externalities then the set of strongly stable networks is equivalent to the set of pairwise stable networks.*

Proof. By definition it holds that any strongly stable network is pairwise stable. Thus, we need to show that any pairwise network is strongly stable. This claim is shown using similar to arguments to Klaus and Walzl (2009)'s Theorem 3.i.

Let μ with associated contracts τ be a network which is blocked by a coalition. It will be shown that for every coalition $t \in T$ that blocks, within the coalition there is a subset of no more than two members that also wishes to block the network. Let $\tilde{\mu}$ be the alternative network that the blocking coalitions implements through a feasible coalition move and τ be the transfers associated with $\tilde{\mu}$.

¹⁷Or, more broadly, by generalized increasing in differences from Legros and Newman (2007).

¹⁸The more extreme case is where all agents have different types, e.g., they exist in a ring with local complementarities, similar to Johnson and Gilles (2000) who assume agents' types are defined on a line. In this setting it may be that stable networks have the property that agents only link with the most similar agents and thus fail to connect with those further away.

¹⁹The lack of gross substitutes is due to the fact that a change in one active link can imply a change in the value of other links. This fact will violate gross substitutes.

632 It is always possible to partition the set of deleted links $\mu \setminus \tilde{\mu}$ into two: (i) a
633 subset denoted $\hat{\mu}$ where for each link ij that can be deleted where one of the two
634 partners can benefit, i.e. it holds that either $z_{ij} + \tau_{ij} - [c_i(\mu) - c_i(\mu \setminus ij)] < 0$ or
635 $z_{ji} + \tau_{ji} - [c_j(\mu) - c_j(\mu \setminus ij)] < 0$; (ii) a subset denoted $\check{\mu}$ where for each link ij neither
636 of the previous two inequalities are satisfied.

637 Suppose that the first partition is non-empty, i.e. $\hat{\mu} \neq \emptyset$. However, as deleting
638 links can be done by a single agent on its own then the move only takes needs the
639 coalition of that agent to delete the link. Thus any part of a coalitional move that
640 only involves profitably removing links can be performed in parts by a coalition with
641 a single agent - therefore this move is also a pairwise block.

642 Thus it remains to be shown that the remaining part of coalitional move also
643 can be performed as a pairwise block, i.e. when forming $\tilde{\mu} \setminus \mu$ and deleting $\check{\mu}$. This
644 part of the coalitional move must entail forming links as no links can be deleted
645 profitably. The set of formed links $\tilde{\mu} \setminus \mu$ can be partitioned into a number of $|\tilde{\mu} \setminus \mu|$
646 feasible submoves of adding a single link while deleting links by each of the agents i
647 and j who form a link. The feasibility for each of the partitioned moves is always true
648 when there is a cost function as moves are unrestricted. It is now argued that each
649 of the partitioned moves are feasible when there is a degree quota. If the network
650 $\mu \cup ij$ is feasible then the move of simply adding the link is feasible. If $\mu \cup ij$ is not
651 feasible, then agents i and j can delete at most one link each and if both μ and $\tilde{\mu}$
652 are feasible then this also feasible as the degree quota is kept.

653 For the coalitional move to $\tilde{\mu}$ it must be that at least at least one link among
654 the implemented links $\tilde{\mu} \setminus \mu$ has a strictly positive value that exceeds the loss from
655 deleting at most one link for each of two agents forming the link. This follows as it
656 is known that deleting one or more links cannot add any value and thus must have
657 weakly negative value and that by definition the total value to the blocking coalition
658 must be positive. As every one of the partitioned moves is feasible, it follows that
659 for every coalitional move there are two agents who can form link while potentially
660 destroying current links and both be better off. In other words, for every coalition
661 that blocks, there is a pairwise coalition that blocks. \square

662 *Proof of Proposition 1..* Suppose the claim is false. Let q be the lowest index for
663 which the condition fail: for all $l < q$ it holds that $\mathcal{X}(\nu_i(\mu)/\{j\})_l \geq \mathcal{X}(\nu_j(\mu)/\{i\})_{l+l^*}$
664 where $l^* = \max(k_j(\mu) - k_i(\mu), 0)$. Thus there are two agents i', j' such that:

$$\begin{aligned} x_{j'} &= \mathcal{X}(\nu_j(\mu))_q, \quad j' \in (\nu_j(\mu) \setminus (\nu_i(\mu) \cup \{i\})), \\ x_{i'} &< \mathcal{X}(\nu_j(\mu))_q, \quad i' \in (\nu_i(\mu) \setminus (\nu_j(\mu) \cup \{j\})). \end{aligned}$$

665 Recall $k^* = \min(k_i(\mu), k_j(\mu))$. The argument why there must exist an agent i' in
666 $\nu_j(\mu)$ but not in $(\nu_j(\mu) \cup \{j\})$ is that $|\{\iota \in \nu_i(\mu) : x_\iota < x_{j'}\}| > |\{\iota \in \nu_j(\mu) : x_\iota < x_{j'}\}|$.

667 This follows as by construction it holds that $|\{\iota \in \nu_i(\mu) : x_\iota < x_{j'}\}| = k^* - q + 1$ and
 668 $|\{\iota \in \nu_j(\mu) : x_\iota < x_{j'}\}| \leq k^* - q$.

669 The agents are such that $x_i > x_j, x_{i'} < x_{j'}$ as well as $ij', ji' \notin \mu$. However,
 670 this fact implies that there is a violation of strong stability: agents i, i', j, j' can
 671 deviate by destroying $\{ij, i'j'\}$ and forming $\{ij', i'j\}$ and thus increase payoffs due to
 672 supermodularity (cf. Equation 2). From Lemma 1 it follows that pairwise stability
 673 is also violated if strong stability is violated. ■

674 *Proof of Proposition 2:* Condition (i) follows from the fact that it is possible for
 675 every agent to be linked with one another. Moreover every link adds value. Thus as
 676 a consequence every link can be formed and will add value both for the pair forming
 677 and it at the aggregate level; thus the unique pairwise and efficient outcome must
 678 be the complete network.

679 We move on to proving condition (ii). Suppose μ is a network where every agent
 680 has $n_{\bar{x}} - 1$ same-type links and $\kappa - n_{\bar{x}} + 1$ cross-type links.

681 Efficiency of μ follows from three facts. Firstly, μ the maximum distance of 2
 682 between any two agents as all same-type links are active and all agents have at
 683 least one cross-type link; thus the potential benefits from indirect connections are
 684 maximized (both for constant and hyperbolic decay). Secondly, the number of same
 685 type links are maximized for all agents and this will maximize the benefits from
 686 direct links; thus there must exactly $n_{\bar{x}} - 1$ same type links. Finally, there can be
 687 no link surplus because violation there exist a network where every agent has $n_{\bar{x}} - 1$
 688 same-type links and $\kappa - n_{\bar{x}} + 1$ cross-type links and thus has no link surplus; this
 689 must have strictly higher aggregate utility as every direct link increases utility.

690 Stability of μ follows from reviewing the feasible deviations. Let there be no
 691 transfers between any agents. Firstly, deleting one or more links is profitable as
 692 it lowers the agents own welfare. Secondly, forming a link requires deletion of one
 693 or more links by both agents. Deleting more links than one will lower the utility
 694 this only the deviations with deletion of a single link are relevant to consider - this
 695 corresponds to substitution of a link. Substituting either a same type link for another
 696 same type link or a cross type link for another cross type provides no change of utility
 697 to the pair of agents deviating. Substituting a cross type link for a same type link
 698 is not feasible. Substituting a same type link for a cross type link will lower the
 699 utility as the indirect benefits are unchanged but the direct benefits must be lower
 700 on aggregate due to supermodularity. ■

701 **Lemma 2.** *For every κ, n such that $n > \kappa$ and $n \cdot \kappa$ is even there exists a network $\mu_{n,\kappa}$
 702 where all agents have exactly κ neighbors. Moreover, if $\kappa \geq 2$ then $\mu_{n,\kappa}$ is connected.*

703 *Proof.* Suppose n is even. Let $\%$ be the modulus operator. We can construct the
 704 following networks.

$$\begin{aligned}\hat{\mu}_{n,\kappa} &= \{ij : i \in \{1, \dots, \frac{n}{2}\}, j \in \{(\frac{n}{2} + i \% \frac{n}{2}), \dots, (\frac{n}{2} + [i + \kappa - 1] \% \frac{n}{2})\}\}, \kappa \leq \frac{n}{2}, \\ \tilde{\mu}_{n,\kappa} &= \begin{cases} \hat{\mu}_{n,\kappa}, & \kappa \leq \frac{n}{2}, \\ \mu_c \setminus \hat{\mu}_{n,n-\kappa-1}, & \kappa > \frac{n}{2}. \end{cases}\end{aligned}$$

705 Letting $\mu_{n,\kappa} = \tilde{\mu}_{n,\kappa}$ is sufficient for n is even. When n is odd we know that κ is
 706 even and thus we can use the following amended procedure instead:

$$\iota_{n,\kappa}(\iota) = \begin{cases} \frac{n-1}{2} + \iota, & \kappa \leq \frac{n-1}{2} \\ \frac{n-1}{2} + (\iota + \kappa) \% \frac{n-1}{2}, & \kappa > \frac{n-1}{2} \end{cases}$$

707

$$\mu_{n,\kappa} = \tilde{\mu}_{n-1,\kappa} \setminus \{ij : i \in \{1, \dots, \frac{\kappa}{2}\}, j = \iota_{n,\kappa}(i)\} \cup \{ij : i = n, j \in (\cup_{\iota \in \{1, \dots, \frac{\kappa}{2}\}} \{\iota, \iota_{n,\kappa}(\iota)\})\}$$

708 We now show that if $\kappa \geq 2$ it follows that $\tilde{\mu}_{n,\kappa}$ is connected. Assume that n is
 709 even and suppose $\kappa \leq \frac{n}{2}$; for any $i \in N : i < \frac{n}{2}$ where $i' = i + 1$ and let $j = \frac{n}{2} + i + 1$
 710 where $ij, i'j \in \tilde{\mu}_{n,\kappa}$; thus for all $i, i' \in \{1, \dots, \frac{n}{2}\}$ it holds that $p_{ii'}(\tilde{\mu}_{n,\kappa}) < \infty$. In
 711 addition, as for any $i \in N : i \leq \frac{n}{2}, j = \frac{n}{2} + i$ it holds that $ij \in \tilde{\mu}_{n,\kappa}$ it follows that $\tilde{\mu}_{n,\kappa}$
 712 is connected. If instead $\kappa > \frac{n}{2}$ then by construction $ii' \in \tilde{\mu}_{n,\kappa}$ if either $\max(i, i') \leq \frac{n}{2}$
 713 or $\min(i, i') > \frac{n}{2}$ as $ii' \notin \hat{\mu}_{n,n-\kappa-1}$. Moreover, for $i \in N : i < \frac{n}{2}$ and $j = \frac{n}{2} + (i + \kappa) \% \frac{n}{2}$
 714 it holds that $ij \notin \hat{\mu}_{n,n-\kappa-1}$; thus $ij \in \tilde{\mu}_{n,\kappa}$. Therefore $\tilde{\mu}_{n,\kappa}$ must be connected.

715 Assume instead that n is odd. By the above argument there are at least two
 716 connected subnetworks consisting of agents in $\cup_{\iota \in \{1, \dots, \frac{\kappa}{2}\}} \{\iota, \iota_{n,\kappa}(\iota)\}$ and agents who are
 717 connected through agent, n , i.e. $N \setminus (\cup_{\iota \in \{1, \dots, \frac{\kappa}{2}\}} \{\iota, \iota_{n,\kappa}(\iota)\})$. If $\kappa \leq \frac{n-1}{2}$ where $i = \frac{\kappa}{2}$,
 718 $i' = \frac{\kappa}{2} + 1$ and $j = \frac{n-1}{2} + \frac{\kappa}{2} + 1$ then $ij, i'j \in \tilde{\mu}_{n,\kappa}$ and thus $\tilde{\mu}_{n,\kappa}$ is connected. If
 719 $\kappa > \frac{n-1}{2}$ where $i = \frac{\kappa}{2}, i' = \frac{\kappa}{2} + 1$ and $j = \frac{n-1}{2} + (\iota + \kappa + 1) \% \frac{n-1}{2}$ then $ij, i'j \in \tilde{\mu}_{n,\kappa}$
 720 and thus $\tilde{\mu}_{n,\kappa}$ is connected. \square

721 **Lemma 3.** Suppose that $\min_{x \in X} n_x > \kappa, \kappa \geq 2$. If $\exists i \in N$ such that:

- 722 a) $|\{i' \in \nu_i(\mu) : x_{i'} = x_i\}| \leq n_x - 2$;
- 723 b) $\min_{i' \in N_x \setminus \nu_i(\mu)} k_{i'}(\mu) = \kappa$, and;
- 724 c) $\max_{i' \in N_x \setminus \nu_i(\mu)} |\{i'' \in \nu_{i'}(\mu) : x_{i''} \neq x\}| = 0$;
- 725 then $\exists i', i'' \in \mu$ such that $i', i'' \notin \nu_i(\mu)$ and $p_{ii''}(\mu \setminus \{i' i''\}) < \infty$

726 *Proof.* Suppose that for $i \in N$ the conditions a)-c) are met but the lemma is not
 727 true. If $i' \in N_x$ and $ii' \notin \mu$ then there must exist some $i'' \in N_x$ such that $i' i'' \in \mu$ and

728 $i'' \notin \nu_i(\mu)$ due to conditions a)-c). If $p_{i'i''}(\mu \setminus \{i'i''\}) < \infty$ then the proof is terminated
 729 so we must assume $p_{i'i''}(\mu \setminus \{i'i''\}) = \infty$.

730 As $p_{i'i''}(\mu \setminus \{i'i''\}) = \infty$ then the network $\mu \setminus \{i'i''\}$ has two components, $\mu', \mu'' \subseteq$
 731 $\mu \setminus \{i'i''\}$, where in each component μ' or μ'' there are at least $\kappa + 1$ agents of type
 732 x (as for any $\iota \in (\nu_{i'}(\mu) \cup \nu_{i''}(\mu))$ it holds that $x_\iota = x$).

733 Agent i can at most be connected to one of i', i'' in $\mu \setminus \{i'i''\}$ as otherwise i', i''
 734 would be connected in $\mu \setminus \{i'i''\}$. Denote the in subnetwork of $\{\mu', \mu''\}$ where i is part
 735 of as $\tilde{\mu}$ and define $\tilde{N} = \{\iota \in N_x \setminus \nu_i(\mu) : \exists \iota' \in N : \iota\iota' \in \tilde{\mu}\}$.

736 Let $\iota_0 \in \arg \max_{\iota \in i', i''} p_{\iota i}$ and iteratively $\iota_l \in \nu_{\iota_{l-1}}(\mu), l \in \mathbb{N}$. Moreover, there must
 737 be a unique path in $\mu \setminus \{i'i''\}$ between any two agents $\iota, \iota' \in \tilde{N}$ as otherwise $i\iota, i\iota' \notin \mu$
 738 but $p_{i\iota'}(\mu \setminus \{i'i''\}) < \infty$; by changing the labels we could denote $i' = \iota$ and $i'' = \iota'$ and
 739 we would have shown the existence of the desired pair of agents.

740 The fact here is a unique path between any two agents in \tilde{N} entails that at level l
 741 or below there are $\sum_{q=0}^l (\kappa - 1)^q$ agents; thus $n_x \geq \sum_{q=0}^l (\kappa - 1)^q$. Let l be the minimal
 742 q such that $\forall \iota \in \tilde{N} : p_{i\iota} \leq q$; as n_x is finite such a q must exist. In addition, as
 743 there is a unique path between agents in μ then any agent $\iota \in \tilde{N} : p_{i\iota_0} = l$ has only
 744 one link, and thus its degree is less than κ (as $\kappa \geq 2$). This violates the condition
 745 that all $i' \in N$ where $x_{i'} = x$ has $k_{i'} = \kappa$. \square

746 *Proof Proposition 3..* The sufficiency of the conditions follows from Lemma 2 which
 747 can be applied to the subset of agents associated with each type as $\forall x \in X : n_x > \kappa$
 748 and $\kappa \cdot n_x \in 2\mathbb{N}$.

749 The necessity of the conditions are straightforward. If either condition i) or iii)
 750 are violated then perfect sorting is not consistent with no-link surplus. If condition
 751 ii) is violated then there can be no type connectivity. \blacksquare

752 *Proof Theorem 1..*

753 **Networks with sorted connectivity are stable** Suppose μ that has sorted
 754 connectivity. We will demonstrate there are thresholds on δ such that μ has pairwise
 755 stability. We're only interested in the minimal thresholds such that for all values of
 756 externalities below those then stability holds. Thus it is sufficient to evaluate the
 757 deviations from the network where the net gains are highest.

758 The losses from breaking a link $ij \in \mu$ can be shown to have bounded from below
 759 such that: $\geq \delta \cdot (1 - Z(x, x))$. Suppose that $n_x = \kappa + 1, x \in X$ then $\{ij \in \mu :$
 760 $x_i = x, x_{i'} = x\}$ is a clique (i.e. any i, i' of type x are linked). This entails that
 761 $p_{ii'}(\mu \setminus \{ii'\}) = 2$ and thus $p_{ii'}(\mu \setminus \{ii'\}) < \infty$. Suppose instead that $n_x > \kappa + 1, x \in X$
 762 then by Lemma 3 there exists some i, i' , both of type x such that $p_{ii'}(\mu \setminus \{ii'\}) < \infty$.

763 Thus when evaluating losses at the threshold we can assume that when deleting some
 764 link ij that i, j are connected in $\mu \setminus \{ij\}$. Although the length of the shortest paths
 765 may increase, there will still be an indirect connection and therefore no loss of utility
 766 for anyone but the two agents who lose their link. Therefore we assume throughout
 767 that when evaluating thresholds if ii' is deleted in a sort-connected network then
 768 only agents i, i' , who must be of same type, will each lose $(1 - \delta) \cdot z(x, x)$ while no
 769 other agents incur a loss.

770 Suppose two agents i, j of distinct types respectively x, \tilde{x} deviate by forming a
 771 link and delete a link each from μ . The total loss for i and j for deleting a link each
 772 is:

$$(1 - \delta) \cdot [z(x, x) + z(\tilde{x}, \tilde{x})] = (1 - \delta) \cdot (\hat{Z}_{x, \tilde{x}} + 1) \cdot Z(x, \tilde{x}).$$

773 The benefit gained for agent i for establishing a link to j is $[1 + (n_{\tilde{x}} - 1) \cdot (1 -$
 774 $\delta)] \cdot z(x, \tilde{x})$. Thus the total benefits gained for i and j from pairwise deviation can
 775 be bounded as follows:

$$\begin{aligned} & [1 + (n_x - 1) \cdot \delta] \cdot z(x, \tilde{x}) + [1 + (n_{\tilde{x}} - 1) \cdot \delta] \cdot z(\tilde{x}, x), \\ &= \langle 1 + [\max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x, \tilde{x}} - 1] \cdot \delta \rangle \cdot Z(x, \tilde{x}). \end{aligned}$$

776 where $\hat{z}_{x, \tilde{x}} = \frac{z(\arg \min_{x, \tilde{x}} n_x, \arg \max_{x, \tilde{x}} n_x)}{Z(x, \tilde{x})}$.

777 We can derive the threshold for pairwise stability, see definition of \hat{Z} from Eq.
 778 (7). :

$$\begin{aligned} (1 - \delta) \cdot (\hat{Z}_{x, \tilde{x}} + 1) \cdot Z(x, \tilde{x}) &= \langle 1 + [\max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x, \tilde{x}} - 1] \cdot \delta \rangle \cdot Z(x, \tilde{x}), \\ (1 - \delta) \cdot (\hat{Z}_{x, \tilde{x}} + 1) &= \langle 1 + [\max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x, \tilde{x}} - 1] \cdot \delta \rangle, \\ \hat{Z}_{x, \tilde{x}} &= \left[\max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x, \tilde{x}} + \hat{Z}_{x, \tilde{x}} \right] \cdot \delta, \\ \delta &= \frac{\hat{Z}_{x, \tilde{x}}}{\max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x, \tilde{x}} + \hat{Z}_{x, \tilde{x}}}. \end{aligned} \tag{A.1}$$

779 Thus we can establish a lower bound for δ^{stab} (i.e. the upper bound in δ for
 780 pairwise stability of μ) by taking the minimum of right-hand-side in Equation A.1;
 781 thus it follows that: $\delta^{stab} = \min_{x, \tilde{x} \in X} \left(\frac{\hat{Z}_{x, \tilde{x}}}{\max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x, \tilde{x}} + \hat{Z}_{x, \tilde{x}}} \right)$. ■

782 **Pairwise stable networks have sorted connectivity when there are two**
 783 **types** We need to show that every pairwise stable network is sort-connected. As
 784 there are only two types it holds that $X = \{\underline{x}, \bar{x}\}$. The outline of the proof is the

we show the conditions in the following order; we begin with perfect sorting, then no link surplus, and finally type connectedness.

787

Perfect sorting We begin by supposing that μ is not perfectly sorted. We will construct a sequence of feasible deviations and show that they are profitable. As this part of the proof has considerable length it will be split into multiple sub-parts with a label that makes it easier to navigate.

792

Sequence of deviations The sequence of feasible deviations will consist of splitting up links between agents of different type and matching at even steps agents of type x and at odd steps agents of type \tilde{x} .

We first define sequences of agents and of deviations as steps $q = 1, 2, \dots, l$ where l is the number of steps. At each step we define the types as $x_q = x, \tilde{x}_q = \tilde{x}$ if q is even else vice versa.

Let the sequence of agent pairs, $i_0 j_0, i_1 j_1, \dots$ be defined as follows. Let agents $i_0, j_0 \in N$ be such that $x_i \neq x_j$ and $ij \in \mu$; such i_0, j_0 must exist if μ is not perfectly sorted. Without loss of generality let $x_{i_0} = x$ and $x_{j_0} = \tilde{x}$ where $x, \tilde{x} \in X$. At step $q \in \mathbb{N}$ let $\iota_q = i_{q-1}$ if q is even else denote $\iota_q = j_{q-1}$. Also let $\eta_q \in \{i_{q-1}, j_{q-1}\} : \eta_q \neq \iota_q$. The advantage of this notation it is easier to define which links are formed between same type agents. Note that by construction we have that $\iota_1 = i_0$ and $\eta_1 = j_0$ as well as $x_{\iota_q} = x_q$ and $x_{\eta_q} = x_q$.

Using the sequence of agent pairs we construct the sequence of deviations as follows.

- At every step $q = 1, \dots, l$ a link is $\iota_q \eta_q (= i_q j_q)$ is broken. We assume that broken links are elements of the original set, i.e. $\iota_q \eta_q \in \mu$ and can only be broken once $\iota_q \eta_q \notin \cup_{m=1}^{q-1} \{\iota_m \eta_m\}$.
- At every step $q = 1, \dots, l$ a link is formed $\iota_q \iota'_q \notin \mu$. This corresponds to $i_q i_{q-1} \notin \mu$ if q is odd and $j_q j_{q-1} \notin \mu$ if q is even. We assume that formed links are not part of the original set μ and can only be formed once $\iota_q \iota'_q \notin \cup_{m=1}^{q-1} \{\iota_m \iota'_m\}$.
- Combining the broken and formed links we get the coalitional move relative to μ :

$$\Delta\mu_q = \mu \cup \{\iota_q \iota'_q\} \setminus \{\iota_q \eta_q, \iota'_q \eta'_q\}, \quad q = 1, \dots, l-1 \quad (\text{A.2})$$

$$\Delta\mu_l = \begin{cases} \mu \cup \{\iota_l \iota'_l\} \setminus \{\iota_l \eta_l, \iota'_l \eta'_l\}, & k_{\iota_l}(\mu) = \kappa \\ \mu \cup \{\iota_l \iota'_l\} \setminus \{\iota_l \eta_l\}, & k_{\iota'_l}(\mu) < \kappa \end{cases} \quad (\text{A.3})$$

814 We note that the above sequence exists as we can always pick $l = 1$ and the
 815 assumption of having a broken link and link formed are satisfied by assumption.

816

817 *Feasible partners* We have defined the sequences of agents and deviations. We
 818 now restrict the set of partners at each step q for agent ι_q for $q = 1, \dots, l$:

$$\begin{aligned} N_q &= \{\iota \in N : x_\iota = x_q\} \\ \hat{N}_q &= \{\iota \in N_q \setminus \{\iota_q\} : \iota_q \notin \mu\} \end{aligned}$$

819 A property of \hat{N}_q is that $\hat{N}_q \neq \emptyset$; this follows as $\min_{\hat{x} \in X} n_{\hat{x}} \geq \kappa + 1$. We will now
 820 show that our restrictions on partner set has implications at each step $q = 1, \dots, l$:

- 821 • Let $\iota'_q \in \hat{N}_q$; this implies that Eq. (A.4) holds. This follows as a violation of
 822 Eq. (A.4) would imply that some agent ι''_q of type x_q would connected only
 823 through η_q ; thus ι_q could link with ι''_q instead of ι'_q and thus ι_q can keep all its
 824 connections to agents who it was already connected to via η_q .

$$|\{\iota \in N : x_\iota = x_q \wedge p_{\iota_q}(\mu) < \infty \wedge p_{\iota_q}(\mu \cup \{\iota_q \iota'_q\} \setminus \{\eta_q \iota_q\}) = \infty\}| = 0 \quad (\text{A.4})$$

- 825 • Suppose that Equation A.5 is violated for for $q \in \{1, \dots, l\}$. This is equivalent to
 826 it holds for any $\iota'_q \in \hat{N}_q$ where $\eta'_q \in \nu_{\iota'_q}(\mu)$ that there is some other $\iota''_q \in \hat{N}_q$ such
 827 that $p_{\iota'_q \iota''_q}(\Delta\mu_q) = \infty$. Let $\iota_q^{(1)} = \iota'_q$. As Equation A.5 must hold for any $\iota'_q \in \hat{N}_q$
 828 we can reproduce the argument iteratively and thus for $\iota_q^{(m)} \in \hat{N}_q, q \in \mathbb{N}$ there
 829 is some $\eta_q^{(m)} \in \nu_{\iota_q^{(m)}}(\mu)$ such that for some $\iota_q^{(m+1)} \in \hat{N}_q \setminus \{\iota_q^{(1)}, \dots, \iota_q^{(m)}\}$ it holds
 830 that $p_{\iota_q^{(1)} \iota_q^{(m+1)}}(\Delta\mu_q) = \infty$. However, as $n < \infty$ it follows that there for some
 831 $q \in \mathbb{N}$ that $\hat{N}_q \setminus \{\iota_q^{(1)}, \dots, \iota_q^{(m)}\} = \emptyset$. Thus let instead $\iota'_q = \iota_q^{(m)}$; for any $\eta'_q \in \nu_{\iota'_q}(\mu)$
 832 there is no $\iota''_q \in \hat{N}_q$ such that $p_{\iota'_q \iota''_q}(\mu) = \infty$. This contradicts that Equation
 833 A.5 is violated for agent $\iota'_q = \iota_q^{(m)}$.

$$|\{\iota \in N : x_\iota = x_q \wedge p_{\iota'_q}(\mu) < \infty \wedge p_{\iota'_q}(\Delta\mu_q) = \infty\}| = 0 \quad (\text{A.5})$$

- 834 • Suppose Eq. (A.4) and (A.5) hold. We can demonstrate a variation of Eq.
 835 (A.4) where $p_{\iota_q}(\Delta\mu_q) < \infty$, i.e. the ι and ι_q are connected despite the deletion
 836 of $\eta'_q \iota'_q$, see Eq. (A.6) below. The argument why Eq. (A.6) holds is as follows.
 837 Suppose $\exists \iota \in N : p_{\iota_q}(\mu \cup \{\iota_q \iota'_q\} \setminus \{\iota_q \eta_q\}) < \infty$ and $p_{\iota_q}(\Delta\mu_q) = \infty$ and $x_\iota = x_q$.
 838 If $p_{\iota_q \iota'_q}(\mu) < \infty$ then as it also holds that $p_{\iota_q \iota'_q}(\Delta\mu_q) < \infty$ it follows that

839 $p_{\iota\iota'_q}(\mu) < \infty$ and $p_{\iota\iota'_q}(\Delta\mu_q) = \infty$ which violates Eq. (A.5). Thus it must
 840 be that $p_{\iota_q\iota'_q}(\mu) = \infty$. Suppose instead $p_{\iota_q\iota'_q}(\mu) = \infty$. Then it must be that
 841 $p_{\iota\eta'_q}(\mu) < \infty$ and thus $p_{\iota\iota'_q}(\mu) < \infty$ as $\iota'_q\eta'_q \in \mu$ which violates that $p_{\iota_q\iota''_q}(\mu) = \infty$.

$$|\{\iota \in N : x_\iota = x_q \wedge p_{\iota\iota_q}(\mu) < \infty \wedge p_{\iota\iota_q}(\Delta\mu_q) = \infty\}| = 0 \quad (\text{A.6})$$

842 *Gains from deviation* We now move on to describing the gains to individuals from
 843 deviating. We assume initial transfers satisfy:

$$-\tau_{i_0j_0} > (1 - \delta) \cdot z(\tilde{x}, \tilde{x}) - [1 + (n_{\tilde{x}} - 1) \cdot \delta] \cdot z(\tilde{x}, x). \quad (\text{A.7})$$

844 The above inequality must hold for either type x or \tilde{x} as we substitute labels for
 845 i, j as well as x, \tilde{x} due to $\Upsilon > 0$.

846 By inserting i, j for ι, η we yield the following expression:

$$\sum_{q=l'}^{l-1} \Delta U_q = \sum_{q=l'}^{l-2} \Delta \hat{U}_q + u_{\iota'_{l-1}}(\Delta\mu_{l-1}) - u_{\iota'_{l-1}}(\mu) + u_{\iota_{l'}}(\Delta\mu_{l'}) - u_{\iota_{l'}}(\mu) \quad (\text{A.8})$$

847 Suppose that at every $q \in \mathbb{N} : q < l$ it holds that $\iota'_q \notin \nu_{\iota_q}(\mu)$, $x_{\iota'_l} = x_l$ and let
 848 $\eta'_l \in \nu_{\iota'_l}(\mu)$.) and let:

$$\Delta U_q = u_{\iota_q}(\Delta\mu_q) - u_{\iota_q}(\mu) + u_{\iota'_q}(\Delta\mu_q) - u_{\iota'_q}(\mu) \quad (\text{A.9})$$

$$\Delta \hat{U}_q = u_{i_q}(\Delta\mu_{q+1_{q:\text{even}}}) - u_{i_q}(\mu) + u_{j_q}(\Delta\mu_{q+1_{q:\text{odd}}}) - u_{j_q}(\mu) \quad (\text{A.10})$$

849 We define the auxiliary term Υ below which is useful for bounding the gains from
 850 deviation. As $\delta < \delta^{stab}$ it follows from Equation A.1 that $\Upsilon > 0$.

$$\Upsilon = (1 - \delta) \cdot [z(\bar{x}, \bar{x}) + z(\underline{x}, \underline{x})] - [1 + (n_{\underline{x}} - 1) \cdot \delta] \cdot z(\underline{x}, \bar{x}) - [1 + (n_{\bar{x}} - 1) \cdot \delta] \cdot z(\bar{x}, \underline{x}). \quad (\text{A.11})$$

851 *Gains for ι_l :* As Eq. (A.4) holds it follows that net gains for ι_q from deleting the
 852 link with η_q while forming a link together with ι'_q can be bounded: the upper bound
 853 of losses is when a connection is lost to all agents of type \tilde{x}_q : $[1 + (n_q - 1) \cdot \delta] \cdot z(x_q, x_q)$;
 854 the lower bound of gains is $(1 - \delta) \cdot z(x_q, \tilde{x}_q)$ as the distance between $\iota_q\iota'_q$ is shortened
 855 to 1.

$$u_{\iota_q}(\mu \cup \{\iota_q\iota'_q\} \setminus \{\iota_q\eta_q\}) - u_{\iota_q}(\mu) \geq (1 - \delta) \cdot z(x_q, x_q) - [1 + (n_q - 1) \cdot \delta] \cdot z(x_q, \tilde{x}_q) \quad (\text{A.12})$$

856 Analogue to the derivation of Ineq. (A.12) the net gains are bounded when Eqs.
 857 (A.5) and (A.6) are satisfied:

$$\min_{\iota \in \{\iota_q, \iota'_q\}} [u_\iota(\Delta\mu_q) - u_\iota(\mu)] \geq (1 - \delta) \cdot z(x_q, x_q) - [1 + (n_q - 1) \cdot \delta] \cdot z(x_q, \tilde{x}_q), \quad (\text{A.13})$$

858 The first and foremost implication of Ineq. (A.13) and the fact that $x_{i_q} \neq x_{j_q}$ is
 859 that:

$$u_{i_q}(\Delta\mu_{q+1_{odd}(q)}) - u_{i_q}(\mu) + u_{j_q}(\Delta\mu_{q+1_{even}(q)}) - u_{j_q}(\mu) \geq \Upsilon. \quad (\text{A.14})$$

860 Another implication of Ineq. (A.7) when combined with Ineq. (A.13) is that:

$$\begin{aligned} u_{\iota_1}(\Delta\mu_1) - u_{\iota_1}(\mu) - \tau_{\iota_1\eta_1} &\geq (1 - \delta) \cdot z(x, x) - [1 + (n_x - 1) \cdot \delta] \cdot z(x, \tilde{x}) - \tau_{i_0j_0} \\ u_{\iota_1}(\Delta\mu_1) - u_{\iota_1}(\mu) - \tau_{\iota_1\eta_1} &\geq \Upsilon \end{aligned} \quad (\text{A.15})$$

861 Furthermore, we can restrict transfers as follows. In order for $\Delta\mu_q$ not to be a
 862 profitable pairwise deviation it must hold that:

$$\begin{aligned} u_{\iota_q}(\mu) + u_{\iota'_q}(\mu) + \tau_{\iota'_q\eta'_q} + \tau_{\iota_q\eta_q} &\geq u_{\iota_q}(\Delta\mu_q) + u_{\iota'_q}(\Delta\mu_q) \\ \tau_{\iota'_q\eta'_q} &\geq \Delta U_q + \tau_{\eta_q\iota_q} \end{aligned}$$

863 We can rewrite the above inequality using that $\iota'_{q-1} = \eta_q, \eta'_{q-1} = \iota_q$ and thus
 864 $\tau_{\iota'_{q-1}\eta'_{q-1}} = \tau_{\eta_q\iota_q}$. We also substitute in Equation A.9 and assume the above inequality
 865 holds for any $q < l$:

$$\begin{aligned} \tau_{\iota'_{l-1}\eta'_{l-1}} &\geq \Delta U_{l-1} + \tau_{\iota'_{l-2}\eta'_{l-2}} \\ \tau_{\iota'_{l-1}\eta'_{l-1}} &\geq \sum_{q=l'}^{l-1} \Delta U_q + \tau_{\iota'_{l'-1}\eta'_{l'-1}} \end{aligned} \quad (\text{A.16})$$

866 As $\tau_{\eta_l\iota_l} = \tau_{\iota'_{l-1}\eta'_{l-1}}$ and $-\tau_{\iota_l\eta_l} = \tau_{\eta_l\iota_l}$ it follows that using Equation A.8:

$$\begin{aligned} -\tau_{\iota_l\eta_l} &\geq \sum_{q=1}^{l-1} \Delta U_q + \tau_{\iota'_{l'-1}\eta'_{l'-1}} \\ &= \sum_{q=1}^{l-2} \Delta \hat{U}_q + u_{\iota'_{l-1}}(\Delta\mu_{l-1}) - u_{\iota'_{l-1}}(\mu) + u_{\iota_1}(\Delta\mu_1) - u_{\iota_1}(\mu) + \tau_{\iota'_0\eta'_0} \\ &= \sum_{q=1}^{l-2} \Delta \hat{U}_q + u_{\eta_l}(\Delta\mu_{l-1}) - u_{\eta_l}(\mu) + u_{\iota_1}(\Delta\mu_1) - u_{\iota_1}(\mu) - \tau_{\iota_1\eta_1} \end{aligned} \quad (\text{A.17})$$

867 *Gains for partners of ι_l : link surplus* We will now examine and find bounds on
 868 the benefits of deviating when we assume that $k_{\iota'_l}(\mu) < \kappa$. As Eq. (A.4) holds it
 869 follows that

$$u_{\iota'_l}(\mu \cup \{\iota_l\iota'_l\} \setminus \{\iota_l\eta_l\}) - u_{\iota'_l}(\mu) \geq (1 - \delta) \cdot z(x_l, x_l),$$

870 and thus $u_{i'_l}(\mu \cup \{\iota_l \iota'_l\} \setminus \{\iota_l \eta_l\}) > 0$.

$$\begin{aligned}
& u_{i_l}(\Delta\mu_l) - u_{i_l}(\mu) - \tau_{i_l \eta_l}, \\
& \geq u_{i_l}(\Delta\mu_l) - u_{i_l}(\mu) + u_{\eta_l}(\Delta\mu_{l-1}) - u_{\eta_l}(\mu) + \sum_{q=1}^{l-2} \Delta\hat{U}_q + u_{i_1}(\Delta\mu_1) - u_{i_1}(\mu) - \tau_{i_1 \eta_1}, \\
& \geq \sum_{q=1}^{l-1} \Delta\hat{U}_q + u_{i_1}(\Delta\mu_1) - u_{i_1}(\mu) - \tau_{i_1 \eta_1}.
\end{aligned} \tag{A.18}$$

871 We now apply Ineqs. (A.14) and (A.15) to the above expression which implies
872 that the gains for i_l from deviating are bounded below by $l \cdot \Upsilon$. As we have that
873 $\Upsilon > 0$ it follows that:

$$u_{i_l}(\mu \cup \{\iota_l \iota'_l\} \setminus \{\iota_l \eta_l\}) - u_{i_l}(\mu) - \tau_{i_l \eta_l} > 0 \tag{A.19}$$

874 Combining that both i_l, i'_l have incentive to deviate it follows their joint deviation
875 is profitable which violates pairwise stability. Thus it must be that $k_{i'_l}(\mu) = \kappa$.

876

Gains for partners of i_l : dropping same type partner with no loss of connectivity
Suppose there exists $i'_l \in \hat{N}_l, i''_l \in \hat{N}_l \setminus \{i'_l\}$ such that $i'_l i''_l \in \mu$, $p_{i'_l i''_l}(\mu \setminus \{i_l \eta_l, i'_l i''_l\}) < \infty$ and $\tau_{i'_l i''_l} \leq 0$. This entails that $u_{i'_l}(\Delta\hat{\mu}_l) - u_{i'_l}(\mu) \geq 0$ where $\Delta\hat{\mu}_l = \mu \cup \{i_l i'_l\} \setminus \{i_l \eta_l, i'_l i''_l\}$. This follows from $u_{i'_l}(\Delta\hat{\mu}_l) - u_{i'_l}(\mu) = u_{i'_l}(\Delta\hat{\mu}_l) - u_{i'_l}(\mu \cap \Delta\hat{\mu}_l) - [u_{i'_l}(\mu \cap \Delta\hat{\mu}_l) - u_{i'_l}(\mu)]$ and $u_{i'_l}(\Delta\hat{\mu}_l) - u_{i'_l}(\mu \cap \Delta\hat{\mu}_l) \geq 1 - z(x, x)$ and $u_{i'_l}(\mu \cap \Delta\hat{\mu}_l) - u_{i'_l}(\mu) = 1 - z(x, x)$. As $\tau_{i'_l i''_l} \leq 0$ it follows that that utility for i'_l is:

$$u_{i'_l}(\Delta\hat{\mu}_l) - u_{i'_l}(\mu) - \tau_{i'_l i''_l} \geq 0.$$

877 And utility for i_l can be bounded as follows using Inequality A.12 for $u_{i_l}(\Delta\hat{\mu}_l) -$
878 $u_{i_l}(\mu)$ as Equation A.4 holds :

$$\begin{aligned}
& u_{i_l}(\Delta\hat{\mu}_l) - u_{i_l}(\mu) - \tau_{i_l \eta_l} \\
& = u_{i_l}(\Delta\hat{\mu}_l) - u_{i_l}(\mu) + \tau_{\eta_l i_l} \\
& \geq \sum_{q=1}^{l-1} \Delta U_q + u_{i_l}(\Delta\hat{\mu}_l) - u_{i_l}(\mu) + \tau_{j_0 i_0} \\
& = \sum_{q=1}^{l-2} \Delta\hat{U}_q + u_{i_l}(\Delta\hat{\mu}_l) - u_{i_l}(\mu) + u_{\eta_l}(\Delta\mu_{l-1}) - u_{\eta_l}(\mu) + u_{i_0}(\Delta\mu_1) - u_{i_0}(\mu) - \tau_{i_0 j_0} \\
& \geq l \cdot \Upsilon \\
& > 0
\end{aligned} \tag{A.20}$$

879 The above inequalities entails that ι_l, ι'_l can deviate profitably pairwise; this is a
 880 violation of pairwise stability and thus cannot be true. Thus there exists no $\iota'_l \iota''_l \in \mu$
 881 such that $\iota'_l \in \hat{N}_l, \iota''_l \in \hat{N}_l \setminus \{\iota'_l\}$ as well as $p_{\iota'_l \iota''_l}(\mu \setminus \{\iota_l \eta_l, \iota'_l \iota''_l\}) < \infty$ and $\tau_{\iota'_l \iota''_l} \leq 0$.

882
 883 *Gains for partners of ι_l : only same type partners.* Suppose that $\forall \iota'_l \in \hat{N}_l : \nexists \eta'_l \in$
 884 $\nu_{\iota'_l}(\mu \setminus \cup_{q=1}^l \{\iota_q \eta_q\}) : x_{\eta'_l} \neq x_l$. This entails that $\forall \iota'_l \in \hat{N}_l : \nexists \eta'_l \in \nu_{\iota'_l}(\mu) : x_{\eta'_l} \neq x_l$
 885 as $k_{\iota'_l}(\mu \setminus \cup_{q=1}^l \{\iota_q \eta_q\}) = k_{\iota'_l}(\mu)$. By Lemma 3 it follows there exists $\iota'_l, \iota''_l \in \hat{N}_l \setminus \nu_i(\mu)$
 886 such that $p_{\iota'_l \iota''_l}(\mu \setminus \{\iota'_l \iota''_l\}) < \infty, \iota'_l \iota''_l \in \mu$ and $\tau_{\iota'_l \iota''_l} \leq 0$ which by the arguments above
 887 cannot be true. Therefore there has to exist some $\iota'_l \in \hat{N}_l$ for which there is an agent
 888 $\eta'_l \in \nu_{\iota'_l}(\mu \setminus \cup_{q=1}^l \{\iota_q \eta_q\})$ where it holds that $x_{\eta'_l} \neq x_l$.

889
 890 *Gains for partners of ι_l : link is already broken.* We shown above that there must
 891 exist some partner η'_q of different type than ι'_q such that $\iota'_q \eta'_q \in \mu$. However, there
 892 can only be a finite number of such links. Therefore, after a number of broken links
 893 there will be only be duplicate links left, i.e. $\iota'_l, \eta'_l \in (\mu \cap \cup_{q=1}^l \{\iota_q \eta_q\})$. That is for
 894 some $l' < l$ it holds that either $\iota_l, \eta_l = \iota_{l'}, \eta_{l'}$ if $l - l'$ is even or $\iota_l, \eta_l = \eta_{l'}, \iota_{l'}$ if $l - l'$
 895 is odd.

896 If $l - l'$ is odd, then $\tau_{\iota'_{l'-1} \eta'_{l'-1}} = -\tau_{\iota'_{l-1} \eta'_{l-1}}$ and therefore we can reduce the In-
 897 equality A.16:

$$\begin{aligned}
 0 &\geq \sum_{q=l'}^{l-1} [u_{\iota_q}(\Delta \mu_q) - u_{\iota_q}(\mu) + u_{\iota'_q}(\Delta \mu_q) - u_{\iota'_q}(\mu)] + 2\tau_{\iota'_{l'-1} \eta'_{l'-1}} \\
 &= \sum_{q=l'}^{l-2} \Delta \hat{U}_q + u_{\iota'_{l-1}}(\Delta \mu_{l-1}) - u_{\iota'_{l-1}}(\mu) + u_{\iota_{l'}}(\Delta \mu_{l'}) - u_{\iota_{l'}}(\mu) + 2\tau_{\iota'_{l'-1} \eta'_{l'-1}} \\
 &= \sum_{q=l'}^{l-2} \Delta \hat{U}_q + 2 \cdot \left\langle u_{\eta'_{l'-1}}(\Delta \mu_{l'}) - u_{\eta'_{l'-1}}(\mu) + \tau_{\iota'_{l'-1} \eta'_{l'-1}} \right\rangle \\
 &= \sum_{q=l'}^{l-2} \Delta \hat{U}_q + 2 \cdot \left\langle u_{\eta'_{l'-1}}(\Delta \mu_{l'}) - u_{\eta'_{l'-1}}(\mu) + \sum_{q=1}^{l'-1} \Delta U_q + \tau_{\iota'_0 \eta'_0} \right\rangle \\
 &= \sum_{q=l'}^{l-2} \Delta \hat{U}_q + 2 \cdot \sum_{q=1}^{l'-1} \Delta \hat{U}_q + 2 \cdot [u_{\iota_1}(\Delta \mu_1) - u_{\iota_1}(\mu) - \tau_{\iota_1 \eta_1}] \\
 &\geq (l + l') \cdot \Upsilon \\
 &> 0,
 \end{aligned}$$

898 thus there must be a feasible pairwise deviation for some agent pair ι_l, ι'_l where

899 $q \in [[1, l]]$.

900 If $l - l'$ is even then $\tau_{l'_{l-1}\eta'_{l-1}} = \tau_{l'_{l'-1}\eta'_{l'-1}}$; thus Inequality A.16 for no pairwise
 901 deviation becomes: $0 \geq \sum_{q=l'}^{l-1} \Delta U_q$. This can in turn be rewritten as follows:

$$0 \geq \sum_{q=l'}^{l-2} \Delta \hat{U}_q + u_{l'_{l-1}}(\Delta \mu_{l-1}) - u_{l'_{l-1}}(\mu) + u_{l'}(\Delta \mu_{l'}) - u_{l'}(\mu)$$

902 Using that $\iota_q = \eta'_{q-1}$ and $\eta'_{l'-1} = \eta'_{l-1}$ we get: $0 \geq \sum_{q=l'}^{l-1} \Delta \hat{U}_q$. Recall that for all
 903 $q \in \mathbb{N} : q < l$ it holds that $\Delta \hat{U}_q \geq \Upsilon$ where $\Upsilon > 0$. Thus there must be a feasible
 904 pairwise deviation.

905 We have now shown that the network μ has perfect sorting.

906

907 No link surplus Suppose that μ has link surplus. This would entail that $\exists i \in N :$
 908 $k_i(\mu) < \kappa$. As $n_x > \kappa$ it must be that $\exists i' \in N : x_{i'} = x_i, ii' \notin \mu$. Suppose that
 909 $k_{i'} < \kappa$ then $\sum_{\iota \in \{i, i'\}} [u_\iota(\mu \cup \{ii'\}) - u_\iota(\mu)] > 0$ and thus ii' can be formed profitably
 910 pairwise. Moreover, as $k_{i'}(\mu) = \kappa$ it follows that $\exists i'' \in \nu_{i'} : ii'' \notin \mu, x_{i''} = x_i$. By
 911 Lemma 3 it follows there exists $\iota, \iota' \in \tilde{N} \setminus \nu_i(\mu)$ such that $p_{\iota'}(\mu \setminus \{\iota'\}) < \infty, \iota' \in \mu$
 912 and $\tau_{\iota'} \leq 0$. This entails that $u_\iota(\mu) - u_\iota(\mu \setminus \{\iota'\}) + \tau_{\iota'} \leq (1 - \delta)z(x, x)$. Moreover,
 913 as $\sum_{j \in \{i, \iota\}} [u_j(\mu \cup \{i\iota\} \setminus \{\iota'\}) - u_j(\mu \setminus \{\iota'\})] \geq (1 - \delta) \cdot Z(x, x)$ it holds that:

$$\sum_{j \in \{i, \iota\}} [u_j(\mu \cup \{i\iota\} \setminus \{\iota'\}) - u_j(\mu)] - \tau_{\iota'} \geq (1 - \delta) \cdot z(x, x)$$

914 .

915 Thus i, ι can deviate profitably pairwise which contradicts pairwise Nash stabil-
 916 ity. Therefore it must be that that μ has no link-surplus.

917

918 Type connected Suppose that μ is not type connected. As μ we have established
 919 perfect sorting and no-link surplus there exist $i, i', j, j' \in N : x_i = x_{i'} = x_j = x_{j'}$ and
 920 $ij, i'j' \in \mu$ and $p_{ii'}(\mu) = \infty$. Without loss of generality we assume that $\tau_{ij}, \tau_{i'j'} \leq 0$
 921 (otherwise we could simply switch identities some i 's and j 's). This entails:

$$\min_{\iota \in \{i, i'\}} [u_\iota(\mu \setminus \{ij, i'j'\}) - u_\iota(\mu)] + \tau_{ij} + \tau_{i'j'} \leq 2(1 - \delta) \cdot z(x, x)$$

922 Also we have that:

$$\min_{\iota \in \{i, i'\}} [u_\iota(\mu \cup \{ii'\} \setminus \{ij, i'j'\}) - u_\iota(\mu \setminus \{ij, i'j'\})] \geq (\kappa + 1) \cdot (1 - \delta) \cdot z(x, x)$$

923 This entails that $\sum_{\iota \in \{i, i'\}} [u_\iota(\mu \cup \{ii'\} \setminus \{ij, i'j'\}) - u_\iota(\mu)] - \tau_{ij} - \tau_{i'j'} \geq \kappa \cdot (1 - \delta) \cdot$
 924 $Z(x, x)$; thus i, i' can deviate profitably. Thus we have established each of the three
 925 properties are necessary for pairwise stability. ■

926 *Proof of Theorem 2.*

927 **Inefficiency of sort-connected networks** We aim to prove that there exists
 928 a threshold δ^{opt} such that if $\delta > \delta^{opt}$ then there exists a network which has higher
 929 aggregate utility than any network with sorted connectivity.

930 Suppose μ is sort-connected and let $\hat{\mu}$ be a bridged, sort-connected network such
 931 that only two distinct types x, \tilde{x} have links across. Denote two agents of type x
 932 who link across types as i, i' and those of type \tilde{x} who link as j, j' . This entails that
 933 $\hat{\mu} = \mu \cup \{ij, i'j'\} \setminus \{ii', jj'\}$. It follows that the loss in aggregate utility is captured
 934 by Eq. (A.21). The gain in aggregate utility follows Eq. (A.22). The aggregate
 935 net-gain in utility is captured by Eq. (A.23).

$$U(\mu \setminus \{ii', jj'\}) - U(\mu) = -(1 - \delta)[Z(x, x) + Z(\tilde{x}, \tilde{x})] \quad (\text{A.21})$$

$$U(\hat{\mu}) - U(\mu \setminus \{ii', jj'\}) = [\delta \cdot (n_x n_{\tilde{x}} - 2) + 2] \cdot Z(x, \tilde{x}) \quad (\text{A.22})$$

$$U(\hat{\mu}) - U(\mu) = -(1 - \delta)[Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x})] + \delta n_x n_{\tilde{x}} \cdot Z(x, \tilde{x}) \quad (\text{A.23})$$

936 The derivative of Eq. (A.23) wrt. δ is $Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x}) + n_x n_{\tilde{x}} \cdot Z(x, \tilde{x})$
 937 Due to supermodularity it holds that $Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x}) > 0$. Therefore,
 938 $U(\hat{\mu}) - U(\mu)$ is monotone increasing in δ . Moreover, $U(\hat{\mu}) - U(\mu) = n_x n_{\tilde{x}} Z(x, \tilde{x}) > 0$
 939 when $\delta = 1$ and $(\hat{\mu}) - U(\mu) = -[Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x})] < 0$ when $\delta = 0$. As both
 940 aggregate losses and gains are continuous in δ it follows by the intermediate value
 941 theorem that there exist a threshold δ^{opt} such that if $\delta > \delta^{opt}$ then $U(\hat{\mu}) > U(\mu)$.

942 For any two types we can compute a threshold $\delta_{x, \tilde{x}}^{opt}$ where gains equal losses as
 943 below. We use definition of \hat{Z} from Eq. (7).

$$\begin{aligned} (n_x \cdot n_{\tilde{x}}) \cdot Z(x, \tilde{x}) \cdot \delta &= 2(1 - \delta) \cdot (\hat{Z}_{x, \tilde{x}}) \cdot Z(x, \tilde{x}), \\ (\hat{Z}_{x, \tilde{x}} + \frac{1}{2}n_x \cdot n_{\tilde{x}}) \cdot \delta &= \hat{Z}_{x, \tilde{x}}, \\ \delta &= \frac{\hat{Z}_{x, \tilde{x}}}{\hat{Z}_{x, \tilde{x}} + \frac{1}{2}n_x \cdot n_{\tilde{x}}}. \end{aligned} \quad (\text{A.24})$$

944 For each pair of types we can compare with the threshold for stability $\delta_{x, \tilde{x}}^{stab}$ from
 945 Eq. (A.1).

$$\begin{aligned}
\delta_{x,\tilde{x}}^{stab} &> \delta_{x,\tilde{x}}^{opt} \\
\left(\frac{\hat{Z}_{x,\tilde{x}}}{\hat{Z}_{x,\tilde{x}} + \max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x,\tilde{x}}} \right) &> \frac{\hat{Z}_{x,\tilde{x}}}{\hat{Z}_{x,\tilde{x}} + \frac{1}{2}n_x \cdot n_{\tilde{x}}} \\
\frac{1}{2}n_x \cdot n_{\tilde{x}} &> \max(n_x, n_{\tilde{x}}) - |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x,\tilde{x}} \\
\frac{1}{2}n_x \cdot n_{\tilde{x}} + |n_x - n_{\tilde{x}}| \cdot \hat{z}_{x,\tilde{x}} &> \max(n_x, n_{\tilde{x}})
\end{aligned}$$

946 As it holds both that $\hat{z}_{x,\tilde{x}} > 0$ and that $n_x \cdot n_{\tilde{x}} > \max n_x, n_{\tilde{x}}$ (because $\min n_x, n_{\tilde{x}} > =$
 947 2) it follows that $\delta_{x,\tilde{x}}^{opt} < \delta_{x,\tilde{x}}^{stab}$. As a consequence it must be that $\min_{x \neq \tilde{x}} \delta_{x,\tilde{x}}^{opt} <$
 948 $\min_{x \neq \tilde{x}} \delta_{x,\tilde{x}}^{stab}$. In other words, this implies that the dominance hold globally for the
 949 threshold $\bar{\delta}^{opt} < \delta^{stab}$. As we only evaluated bridged, sort-connected networks where
 950 two types link across there may exist lower thresholds for optimality $\delta^{opt} \leq \bar{\delta}^{opt}$. By
 951 construction it holds that $\delta^{opt} < \delta^{stab}$.

952 **Efficiency of networks** Our next aim is to show the following properties when
 953 there are only two types: (i) $\delta^{opt} = \bar{\delta}^{opt}$; (ii) for $\delta \leq \delta^{opt}$ it holds that any sort-
 954 connected network is efficient; and (iii) for $\delta \geq \delta^{opt}$ any bridged, sort-connected
 955 network is efficient.

956 Property (i). As there are only two types it follows that the only kind of bridged,
 957 sort-connected network is one where two agents of each of the two types break a
 958 link and form new links across. The threshold for optimality for this bridged, sort-
 959 connected can be computed from Eq. (A.24).

960 In order to prove properties (ii) and (iii) we want to show there are only two
 961 classes of networks which can be efficient: the sort-connected and the bridged, sort-
 962 connected. We begin by noting that utility under hyperbolic decay (from Equation
 963 3) can be expressed as:

$$w_{ij}(\mu) = (1 - \delta) \mathbf{1}_{=1}(p_{ij}(\mu)) + \delta \cdot \mathbf{1}_{\in[1,\infty)}(p_{ij}(\mu)). \quad (\text{A.25})$$

964 Thus total utility from the network has the following form:

$$U(\mu) = \sum_{i \in N} \sum_{j \in N, j \neq i} [(1 - \delta) \cdot \mathbf{1}_{=1}(p_{ij}(\mu)) + \delta \cdot \mathbf{1}_{\in[1,\infty)}(p_{ij}(\mu))] \cdot z(x_i, x_j). \quad (\text{A.26})$$

965 The form for aggregate utility in Equation A.26 has the advantage that it is easier
 966 to perform optimization on. From inspection we see that if a network is connected

967 then indirect term in the weights, $\delta \cdot \mathbf{1}_{\in[1,\infty)}(p_{ij}(\mu))$, is one for all edges, and as a
 968 consequence the aggregate utility attains its maximal value.

969 We first restrict ourselves to look at perfectly sorted networks. If it holds that each
 970 subnetwork $\mu_x \subseteq \mu$ consisting of all links within a given type is connected then the
 971 argument made above, that the aggregate utility from indirect links (i.e. stemming
 972 from $\delta \cdot \mathbf{1}_{\in[1,\infty)}(p_{ij}(\mu_x)) = 1$ for $x_i = x_j, i \neq j$ in Equation A.26), is maximized
 973 (conditional on perfect sorting). Finally, it must be that each subnetwork has no
 974 link surplus. This follows as there exists a subnetwork $\tilde{\mu}_x$ with no link surplus which
 975 is connected from Lemma 2. Thus any link surplus would imply inefficiency of μ_x
 976 as it would hold that the number of links between type x would be lower than
 977 the possible, i.e. $\sum_{ij \in \tilde{\mu}_x} \mathbf{1}_{=1}(p_{ij}(\tilde{\mu}_x)) > \sum_{ij \in \mu_x} \mathbf{1}_{=1}(p_{ij}(\mu_x))$, and thus provide lower
 978 welfare by Equation A.26. As any network with sorted connectivity obtains exactly
 979 the same utility we know that this set constitutes the set of networks with highest
 980 aggregate utility among networks with perfect sorting. We know from Proposition 3
 981 that the set of networks with sorted connectivity is non-empty. We have thus shown
 982 that the set of networks with sorted connectivity are efficient among perfectly sorted
 983 networks.

984 We proceed with analyzing efficient networks among those without perfect sort-
 985 ing. Assume that a network μ is not perfectly sorted. Suppose further that μ is con-
 986 nected. Then the total utility from indirect links is maximized as $\mathbf{1}_{\in[1,\infty)}(p_{ij}(\mu)) = 1$
 987 for every $i \neq j$. The utility accruing from (direct) links stems from the term
 988 $\mathbf{1}_{=1}(p_{ij}(\mu))$ in Equation A.26. Due to supermodularity the utility from (direct) link-
 989 ing will be maximized if there is perfect sorting, however, this is not feasible as we
 990 require links across the two types. The minimal required links across types are two
 991 for every type. This follows as at least one link across types is required and thus the
 992 number of same type links must be at least one lower. Therefore, the highest attain-
 993 able number of links within same type is $\frac{n_x \kappa}{2} - 1$ with two links across. Having $\frac{n_x \kappa}{2} - 1$
 994 same type links and two cross-type links as well as type connectivity correspond ex-
 995 actly to the definition of bridged, sort-connected networks. Any other network which
 996 is not perfectly sorted can also at most have $\frac{n_x \kappa}{2} - 1$ same type links. This implies that
 997 the bridged, sort-connected has maximal benefits possible from direct (links) subject
 998 to being perfectly sorted. Due to being connected it also has the maximum num-
 999 ber of indirect benefits. It remains to show that the set of bridged, sort-connected
 1000 networks is non-empty; we can construct a bridged, sort-connected network from a
 1001 sort-connected network as $\hat{\mu} = \mu \cup \{ij, i'j'\} \setminus \{ii', jj'\}$ where $x_i = x_{i'}, x_j = x_{j'}, x_i \neq x_j$
 1002 and μ is sort-connected. We verify that by construction $\hat{\mu}$ has the feature of
 1003 being connected (as the subnetworks for each type are connected if we choose each
 1004 subnetwork using Lemma 2) and there are exactly $\frac{n_x \kappa}{2} - 1$ links of same type links

for each type. Thus, we have determined that the bridged, sort-connected network must maximize aggregate utility among networks that are not-perfectly sorted.

We have established there are only two networks which can be efficient. We know from Eq. (A.24) that if $\delta < \delta^{opt}$ then the payoff from sort-connected network exceeds the payoff from bridged, sort-connected networks and vice versa. Therefore, when $\delta \leq \delta^{opt}$ then the sort-connected network is efficient, however, when $\delta \geq \delta^{opt}$ then the bridged, sort-connected network is efficient. ■

Proof Proposition 4.. Let $\mu \in \hat{M}$ and $\delta < \delta^{stab}$. By construction there exists a network $\tilde{\mu}$ which has higher aggregate utility. Let the two pairs of agents ii', jj' be agents such that $\tilde{\mu} = \mu \cup \{ij, i'j'\} \setminus \{ii', jj'\}$ and $x_i = x_{i'} = x$ and $x_j = x_{j'} = x$. Specify a link-contingent contract to i, j where $\hat{\mu} = \mu \cup \{ij\} \setminus \{ii', jj'\}$ such that:

$$\forall u' \in \{ij, i'j'\} : \quad C_{u'} + C_{i'u} \geq \frac{1}{2}[Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x})], \quad (\text{A.27})$$

$$\forall u' \notin \{ij, ji, i'j', j'i'\} : \quad C_{u'} = 0. \quad (\text{A.28})$$

By Theorem 1 we know that μ is pairwise stable. Pairwise stability implies that $\frac{1}{2}[Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x})] > u_i(\mu) - u_i(\hat{\mu}) + u_j(\mu) - u_j(\hat{\mu})$ as deviation is not profitable. Using this fact together with Inequality A.27 it follows that:

$$C_{ij} + C_{ji} > u_i(\mu) - u_i(\hat{\mu}) + u_j(\mu) - u_j(\hat{\mu}).$$

The above inequality entails agents i, j are a blocking coalition that can gain by deviating to $\hat{\mu}$; this blocking move is also the only profitable move for i, j due to pairwise stability of μ and Equation A.28.

In network $\hat{\mu}$ agents i', j' have an incentive to form a link with one another as both have surplus link capacity (i.e. degree below the quota) and forming a link is profitable from Inequality A.27. Moreover, we show in the following that this move is the one that ensures the highest aggregate net benefits to i', j' .

We begin with showing that linking across types to other agents of type x, \tilde{x} is not profitable. Suppose i' links across types to another agent $j'' \in \{i' \neq j' : x_{i'} = x_{j''}\}$. First, note the pairwise deviation from μ to form $i'j''$ is unprofitable (due to pairwise stability), thus it is less profitable than forming $i'j'$ from μ (which is profitable by Inequality A.27). Second, the net-increase in value of the pairwise deviation to form $i'j'$ over $i'j''$ increases from μ to $\hat{\mu}$ - this is true as j' loses the link with i from μ while j'' has an unchanged number - thus j' will have a weakly lower opportunity cost of deleting links in $\hat{\mu}$. The same argument can be applied to j' for $i'' \in \{i' \neq i : x_{i'} = x_{i''}\}$.

We turn to showing that linking to other agents of same type (staying sorted) is not more profitable as well. Suppose i' and j' link to same types as themselves

1036 respectively, i.e. $i'' \in \{\iota \neq i' : x_\iota = x_{i'}\}$ and $j'' \in \{\iota \neq j' : x_\iota = x_{j'}\}$. Suppose $ii'' \in \mu$
 1037 then no feasible pairwise moves to same type can exist in $\hat{\mu}$ as the move can only
 1038 involve deleting links; same is true if $jj'' \in \mu$. Thus instead we use $ii'', jj'' \notin \mu$. It
 1039 must be that any pairwise deviation forming either ii'' or jj'' from μ is unprofitable
 1040 (as μ is pairwise stable); this implies that for any $\iota \in \nu_{i''}(\hat{\mu})$ and $\iota' \in \nu_{j''}(\hat{\mu})$ it holds
 1041 that:

$$\begin{aligned} u_{i'}(\hat{\mu} \cup \{i'i''\} \setminus \{i''\iota\}) - u_{i'}(\hat{\mu}) + u_{i''}(\hat{\mu} \cup \{i'i''\} \setminus \{i''\iota\}) - u_{i''}(\hat{\mu}) - \tau_{i''\iota} &\leq z(\text{A.29}) \\ u_{j'}(\hat{\mu} \cup \{j'j''\} \setminus \{j''\iota'\}) - u_{j'}(\hat{\mu}) + u_{j''}(\hat{\mu} \cup \{j'j''\} \setminus \{j''\iota'\}) - u_{j''}(\hat{\mu}) - \tau_{j''\iota'} &\leq z(\text{A.30}) \end{aligned}$$

1042 As $u_{i'}(\tilde{\mu}) - u_{i'}(\hat{\mu}) + u_{j'}(\tilde{\mu}) - u_{j'}(\hat{\mu}) = z(x, \tilde{x}) + z(\tilde{x}, x)$ it follows that

$$u_{i'}(\tilde{\mu}) - u_{i'}(\hat{\mu}) + u_{j'}(\tilde{\mu}) - u_{j'}(\hat{\mu}) + \mathcal{C}_{i'j'} + \mathcal{C}_{j'i'} > z(x, x) + z(\tilde{x}, \tilde{x}).$$

1043 The above inequality implies together with Inequalities A.29 and A.30 that the
 1044 total gains for i' and j' exceeds the total value that could be generated from alter-
 1045 native deviations. Thus there are two pairwise moves from μ to $\hat{\mu}$ and from $\hat{\mu}$ to $\tilde{\mu}$
 1046 which both provide strictly higher utility to the deviating agents.

1047 Pairwise stability follows from three arguments. First, all deviations among
 1048 agents where only links in $\tilde{\mu} \cap \mu$ are deleted will provide at most the same value
 1049 in $\tilde{\mu}$ that the deviations did in μ - this follows as these agents all have the same links
 1050 and in $\tilde{\mu}$ all agents are connected in $\tilde{\mu}$ and thus only direct links matter. This upper
 1051 limit too gains from deviations implies none of these moves can be profitable as they
 1052 were unprofitable from μ . Second, deviations that involve deletion of links in $\tilde{\mu} \setminus \mu$
 1053 are shown above to provide strictly higher value than any other deviations - thus
 1054 deviating from $\tilde{\mu}$ must also provide strictly lower value. ■

1055 *Proof of Proposition 5..* Under asymptotic independence it follows that average per
 1056 agent utility for type x under asymptotic perfect sorting converges to (using a geo-
 1057 metric series):

$$\frac{(\kappa - 1) \delta}{1 - (\kappa - 1) \delta} z(x, x)$$

1058 Let $\omega_{x\tilde{x}} = \kappa \cdot \mathbb{E}[\delta^{p_{ij}} | x_i = x, x_j = \tilde{x}]$. Suppose that for two types, x, \tilde{x} there is not
 1059 perfect sorting, and in particular there is some mixing between them, i.e. $\omega_{x\tilde{x}} > 0$;
 1060 the average per agent utility is:

$$\left[\frac{(\kappa - 1) \delta}{1 - (\kappa - 1) \delta} - \omega_x \right] \cdot z(x, x) + \omega_x \cdot z(x, \tilde{x}).$$

Each agent will almost surely have κ links as it is assumed that each link adds positive value and there are asymptotic infinite agents (only a finite number can then not fulfill the degree quota).

As we have a finite set of types we can assume then for large populations there is a subset of types, $\hat{X} \subseteq X$, where for every type $x \in \hat{X}$ it holds that there is an asymptotic strictly positive share of the total number of agents of that type, i.e., $\lim_{n \rightarrow \infty} (|\{i \in N_n\}_{x_i=x}|/n) > 0$. If there is only one such type, i.e. $|\hat{X}| = 1$, then asymptotic perfect sorting follows by assumption as the asymptotic number of links is κ .

For any two types $x, \tilde{x} \in \hat{X}$ which are mixing their average utility is:

$$\frac{(\kappa - 1) \delta}{1 - (\kappa - 1) \delta} \left[\frac{n_x \cdot z(x, x) + n_{\tilde{x}} \cdot z(\tilde{x}, \tilde{x})}{n_x + n_{\tilde{x}}} \right] - \frac{1}{2} \cdot \left[\frac{n_x \cdot \omega_{x\tilde{x}}}{n_x + n_{\tilde{x}}} \right] \cdot [Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x})].$$

As there is supermodularity it follows that $Z(x, x) + Z(\tilde{x}, \tilde{x}) - 2Z(x, \tilde{x}) > 0$ and thus mixing must decrease utility. The same argument can be applied by mixing between multiple types. ■

Appendix B. Supplementary appendix: finite poulation and constant decay in spillovers

This appendix extends the analysis of sorted networks with finite number of agents to a setting where decay is constant. We prove properties of stability and efficiency for a sub-class of sort-connected networks under constant decay. Specifically we show that certain network with sorted connectivity are pairwise stable for low to moderate spillovers. We also show that these network are suboptimal for moderate to high spillovers.

The appendix is split into two sub-appendices, Appendix B.1 which contains the main results and Appendix B.2 which only contains auxiliary results.

Appendix B.1. Suboptimal sorting in local trees

We begin by describing the sub-class of sort-connected networks. Informally put, the sub-class has the added requirement that networks are not only connected within each type, but also resembles a certain tree structure. We define a *tree* as a network where every pair of agents are connected by a unique path. The structure of each subnetwork is such that from the perspective of every agent (i.e. the ego-network) each subnetwork appears as a tree locally. That is, the network becomes a tree if we remove all links for the agents furthest away from the considered agent which are

not on their shortest path(s) to the considered agent. Therefore the networks have a local tree structure but not a global one.

The formal definition of local trees is described below. The definition employs the network *diameter* which is the maximum distance between any two agents, i.e. $m(\mu) = \sup_{i,j \in N} p_{ij}(\mu)$.

Definition 11. A network μ is a **local tree** when each agent i has κ links where:

- for each other agent $j \neq i$ at distance $p_{ij}(\mu) \leq m_{n,\kappa} - 2$ there are $\kappa - 1$ links between agent j and j' such that j' is one step further away, i.e. $p_{ij}(\mu) = p_{ij'}(\mu) - 1$;
- the network diameter $m(\mu) = m_{n,\kappa}$,

$$m_{n,\kappa} = \arg \min_m \{m : \sum_{l=1}^m (\kappa(\kappa - 1)^{l-1}) + 1 \geq n\}. \quad (\text{B.1})$$

The structure of local trees entails that each agent has $\kappa \cdot (\kappa - 1)^{p-1}$ agents at distance $p < m$, where $m = m_{n,\kappa}$. At distance $p = m$ there are $n - \sum_{l=1}^{m-1} \kappa \cdot (\kappa - 1)^{l-1}$ (all remaining agents). This structure implies that every agent's utility is maximized subject to the constraint of all agents having at most κ links;²⁰ a side effect is that utility before transfers is symmetric.

A necessary condition for local trees to exist is that there is no link surplus, i.e. degree quota is binding ($\forall i \in N : k_i = \kappa$). Note this binding condition is only possible when $n \cdot \kappa$ is even.

When a local tree network fulfills $n = \sum_{l=1}^m \kappa \cdot (\kappa - 1)^{l-1}$ then it is an *exact local tree*. See the next sub-appendix for an elaborate treatment of structure of exactly local trees. Two subclasses of exact local trees which are worth mentioning. The first is a network known as a cycle or a ring. The cycle is characterized by having a minimal possible degree quota ($\kappa = 2$) among local trees and a maximal diameter ($m = \lceil \frac{n-1}{2} \rceil$). The second is a *clique* where all agents are linked, i.e. the complete network. Cliques have maximal degree quotas ($\kappa = n - 1$) and minimal diameters ($m = 1$). Both subclasses has a network which exists for any n . Note that in Example 1 each of the two components is both a cycle and a clique. Note that there exist non-trivial networks beyond the cycle and the clique.²¹

²⁰The maximization of utility follows from the observation that each agent has at most κ links, so at distance p there can be at most $\kappa \cdot (\kappa - 1)^{p-1}$ agents.

²¹An example is $\{i_1 i_2, i_1 i_3, i_1 i_4, i_2 i_5, i_2 i_6, i_3 i_7, i_3 i_8, i_4 i_9, i_4 i_{10}, i_5 i_7, i_5 i_9, i_6 i_8, i_6 i_{10}, i_7 i_9, i_8 i_{10}\}$ when $n = 10, \kappa = 3$ and $N = \{i_1, i_2, \dots, i_{10}\}$.

1120 In order to derive our results it is necessary to restrict ourselves to a subset of
 1121 local trees. The subset are those local trees where the deletion of links leads to equal
 1122 losses to both of agents whose link is deleted; thus we refer to these local trees as
 1123 having symmetric losses:

1124 **Definition 12.** *A local tree μ has **symmetric losses** when at every distance $p =$
 1125 $1, \dots, m$ it holds that $|\{i \in N : p_{\iota i}(\mu \setminus \{\iota \iota'\}) = p\}| = |\{i \in N : p_{\iota' i}(\mu \setminus \{\iota \iota'\}) = p\}|$.*

1126 Whether or not symmetric losses is a generic property for all local trees is an open
 1127 question. However, in simulations that we perform it holds all network configurations
 1128 which are local trees up to size $n = 10$ have symmetric losses (see result below and
 1129 proof for exhibition of examples). In addition, for size up to $n = 16$ it has been
 1130 shown to hold for any networks examined in the simulation.

1131 A generalization of stable but suboptimal sorting under constant decay is ex-
 1132 pressed below. While allowing for constant decay rather than hyperbolic it the set
 1133 of networks are further restricted.

1134 **Theorem 3.** *Suppose there is supermodularity, a degree quota κ and each type has
 1135 equal number of agents. It follows that any network which is sort-connected and
 1136 consist of symmetric local trees is also: (i) pairwise stable if $\delta < \delta^{stab}$; and, (ii)
 1137 inefficient if $\delta > \delta^{opt}$. The thresholds satisfy $\delta^{opt}, \delta^{stab} \in (0, 1)$ where $\delta^{opt} < \delta^{stab}$*

1138 *Proof.* We show properties (i) and (ii) together. Let μ be a network which is perfectly
 1139 sorted into $|X|$ components, one for each type. Each component is a local tree with
 1140 $n/|X|$ agents. Let there be no transfers between any agents.

1141 As each subnetwork for a given type is a local tree it is stable against deviations by
 1142 agents of the same type - this follows as local trees provides maximal possible benefits
 1143 among feasible structures of the subnetwork for all agents in the subnetwork. Thus
 1144 only two agents of different types may have a profitable deviation which is feasible.

1145 Let ι, j be agents of respectively types x and \tilde{x} . These two agents can deviate by
 1146 each deleting a link to ι' and j' respectively while jointly forming a link. The new
 1147 network resulting from deletion is denoted $\hat{\mu} = \mu \setminus \{\iota \iota', j j'\}$. The move resulting from
 1148 deletion and forming a link is denoted $\check{\mu} = \hat{\mu} \cup \{\iota j\}$. An alternative network is $\tilde{\mu}$,
 1149 the type-bridged network of μ , where the links $\iota \iota', j j'$ are removed while the links
 1150 $\iota j, \iota', j'$ have been formed; thus $\tilde{\mu} = \hat{\mu} \cup \{\iota j, \iota' j'\}$.

1151 Define the gross loss of benefits for i as $u_i(\hat{\mu}) - u_i(\mu)$ while the gross gains are
 1152 $u_i(\tilde{\mu}) - u_i(\hat{\mu})$. There must exist a threshold of externalities $\delta^{stab} \in (0, 1)$ where μ is no
 1153 longer pairwise stable as cost of deviation monotonically decreases and approaches
 1154 zero as $\delta \rightarrow 1$ while gains are monotonically increasing. The monotonicity of losses is
 1155 a consequence of the fact that gross loss consists of shortest paths from μ , where $\iota \iota'$ is

1156 included in the shortest path, which have longer length in $\hat{\mu}$ and thus are discounted
 1157 more. Therefore the gross loss is mitigated by a higher δ as the longer shortest paths
 1158 are punished less. The monotonicity of gains follows as the gains consist of new
 1159 shortest paths to agents of type \tilde{x} through ιj and $j' \iota'$ the value of these increases for
 1160 higher δ .

1161 Exploiting the that Fact 1 and 2 from Appendix Appendix B.2 hold for local
 1162 trees it follows that for any other agent i of type x (i.e. i is in $N \setminus \{\iota, \iota'\}$ and $x_i = x$):

$$u_i(\tilde{\mu}) - u_i(\mu) > \delta^{\min(p_{i\iota}(\tilde{\mu}), p_{i\iota'}(\tilde{\mu}))} [u_\iota(\tilde{\mu}) - u_\iota(\mu)].$$

1163 Aggregating for all agents this implies:

$$U(\tilde{\mu}) - U(\mu) > [u_\iota(\tilde{\mu}) - u_\iota(\mu)] \cdot \sum_{x_i=x} \delta^{\min(p_{i\iota}(\tilde{\mu}), p_{i\iota'}(\tilde{\mu}))} + [u_j(\tilde{\mu}) - u_j(\mu)] \cdot \sum_{x'_i=\tilde{x}} \delta^{\min(p_{ij}(\mu), p_{ij'}(\mu))}.$$

1164 where $m = m_{n,\kappa}$. The inequality above implies the following: if $U(\tilde{\mu}) - U(\mu) = 0$
 1165 then $u_\iota(\tilde{\mu}) - u_\iota(\mu) + u_j(\tilde{\mu}) - u_j(\mu) < 0$; $U(\tilde{\mu}) - U(\mu) > 0$ when $u_\iota(\tilde{\mu}) - u_\iota(\mu) +$
 1166 $u_j(\tilde{\mu}) - u_j(\mu) = 0$. It can also be argued that there must exist a threshold, δ^{opt} ,
 1167 such that when $\delta = \delta^{opt}$ then $U(\tilde{\mu}) - U(\mu) = 0$ and that $\delta^{opt} < \delta^{stab}$. This follows as
 1168 $U(\tilde{\mu}) - U(\mu) < 0$ for $\delta = 0$ and $U(\tilde{\mu}) - U(\mu) > 0$ when $u_\iota(\tilde{\mu}) - u_\iota(\mu) + u_j(\tilde{\mu}) - u_j(\mu) = 0$
 1169 as well as continuity of $U(\tilde{\mu}) - U(\mu)$ in δ .

1170 This entails that for $\delta > \delta^{opt}$ then $\tilde{\mu}$ provide higher aggregate payoff. Moreover
 1171 we showed previously that for $\delta < \delta^{stab}$ then μ is pairwise (Nash) stable. Thus we
 1172 have proven properties (i) and (ii).
 1173 □

1174 For constant decay the thresholds governing when sorting is respectively subop-
 1175 timal and stable, i.e. $\delta^{opt}, \delta^{stab}$, can be determined explicitly by solving polynomial
 1176 equations for every deviation. Moreover, for exact local trees there is a unique solu-
 1177 tion. In Figure B.3 the two thresholds from Theorem 3, $\delta^{opt}(\hat{Z}), \delta^{stab}(\hat{Z})$.

1178 The plots in Figure B.3 are made for variations of exact local trees. The upper
 1179 plots corresponds to cliques with various sizes. The lower plot have fixed degree quota
 1180 ($\kappa=100$) and the threshold is simulated using pattern in utility that is demonstrated
 1181 in Appendix Appendix B.2. The plots show the scope for inefficiency, i.e. the
 1182 gap between $\delta^{opt}(\hat{Z}), \delta^{stab}(\hat{Z})$, increases with the number of agents involved. This
 1183 makes sense intuitively as the two agents forming the link will fail to account for an
 1184 increasing number of indirect connections between the two groups. As the number of
 1185 indirect connections increases at with the squared with total number of agents then
 1186 larger populations will lead to larger gaps of inefficiency.

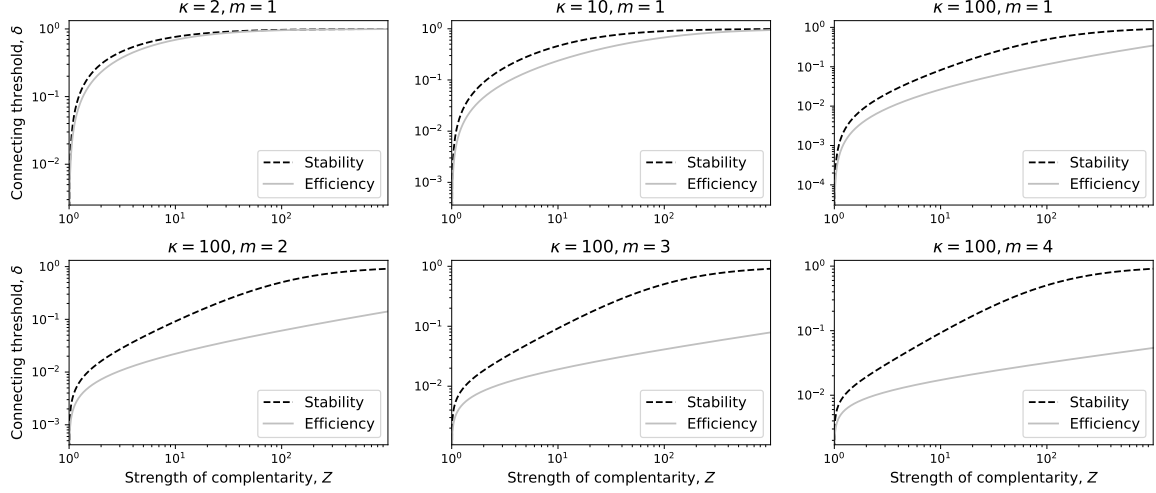


Figure B.3: *Visualization of thresholds for connecting from Theorem 3.*

The upper diagrams correspond to cliques and the lower ones to exact local trees (where thresholds stem from Equations B.4, B.5, B.10, B.11).

Appendix B.2. Local trees

This sub-appendix provides auxiliary results for deriving the generalization of suboptimal sorting. We begin our focus on exact local trees and subsequently more generally in local tree networks, see Definition 11 in the previous sub-appendix.

We will examine a generic network μ which is perfectly sorted and assume that the subset of links for each type is a component that can be classified as either a local tree or an exact local tree. Let networks μ_x and $\mu_{\tilde{x}}$ be the components associated with respectively types $x, \tilde{x} \in X$. We will focus on three particular moves:

- *Pairwise deletion of a link*: Suppose two links $\iota\iota', jj' \in \mu$ are deleted and agents ι and j have respectively type x and \tilde{x} ; thus the two links are not from the same component. Let the new network that results from removal of the links be denoted $\hat{\mu} = \mu \setminus \{\iota\iota', jj'\}$.
- *Pairwise formation of a link across types*: This move presumes that both agents are also deleting a link. We denote this as a move where agents ι and j form a link: $\check{\mu} = \hat{\mu} \cup \{\iota j\}$.
- *Double pairwise formation of a link across types*: When two links are formed across types in μ this corresponds to a non-pairwise deviation as it requires

four coalition members. We denote this as a move where both agents ι and j as well as ι' and j' form a link: $\tilde{\mu} = \hat{\mu} \cup \{\iota j, \iota' j'\}$.

Finally let i denote a generic agent of type x . Let the shortest path in μ from i to either ι or ι' be denoted \hat{p}_i where $\hat{p}_i = \min(p_{i\iota}(\hat{\mu}), p_{i\iota'}(\hat{\mu}))$. When $\hat{p}_i = 0$ then either $i = \iota$ or $i = \iota'$.

Basic properties. We exploit that μ is a local tree (see Definition 11). Throughout the remainder of the paper let $m = m_{n,\kappa}$ (see Equation B.1). We express each agent's number of paths of length p as a function of the number of agents and the degree quota:

$$\#_i^p(\mu) = \kappa(\kappa-1)^{p-1} - \mathbf{1}_{=m}(p) \cdot \Delta\#(n, \kappa), \quad \Delta\#(n, \kappa) = \sum_{l=1}^m (\kappa \cdot (\kappa-1)^{l-1}) - n, \quad (\text{B.2})$$

where $\mathbf{1}_{=m}(p)$ is the Dirac measure of whether $p = m$. Using the local tree structure we can express utility without transfers of each agent:

$$u_i(\mu) = \sum_{l=1}^m \#_i^l(\mu) \cdot \delta^l \cdot z(x, x).$$

Exact local trees

Recall exact local trees are local trees where $\Delta\#(n, \kappa) = 0$. We will argue that this entails that exact local trees have the essential property that for every pair of agents there is a unique shortest path of at most length m and the number of paths for every agent is prescribed by Equation B.2. This can be deduced as follows.

Note first that the fact that the number of walks with at most length m starting in a given agent i cannot exceed $\sum_{p=1}^m \#_i^p(\cdot)$. Recall also that local trees has the property that all agents are reached within distance m . Moreover exact local trees has the property that for any agent i it holds that $n - 1 = \sum_{p=1}^m \#_i^p(\mu)$; thus every shortest path with distances less than or equal to m must be a unique path between the two particular agents.

The uniqueness and countability of paths can be used to infer the losses when links are either removed or added to an exact local tree.

Exact local trees - loss from deletion. In order to examine the impact of deletion of a link it is sufficient to analyze what happens to one component of types. This is sufficient as other components as the conclusions are valid for all.

The deletion of link $\iota\iota'$ implies that any pair of agents i, i' whose (unique) shortest path in μ includes the link $\iota\iota'$ will have a new shortest routing path. For exact local

1233 trees we can exactly determine the length of the new path. Let i be the agent
 1234 whose distance to ι is least and let i' be the agent whose distance to ι' is least, i.e.
 1235 $p_{i\iota}(\mu) < p_{i\iota'}(\mu)$ and $p_{i'\iota'}(\mu) < p_{i'\iota}(\mu)$.

1236 First when link $\iota\iota'$ is deleted we can show there is no shortest path between i and
 1237 i' in $\hat{\mu}$ with length below $2m - \hat{p}_i - \hat{p}_{i'}$; that is there is no ii' whose shortest path
 1238 in μ includes $\iota\iota'$ such that $p_{ii'}(\hat{\mu}) < 2m - \hat{p}_i - \hat{p}_{i'}$. Suppose this was not true. Then
 1239 there would exist an agent j who (1) is on the new shortest path between i and i'
 1240 in $\hat{\mu}$ and (2) whose shortest path to agents ι and ι' does not include the link $\iota\iota'$ and
 1241 (3) such that

$$\begin{aligned} p_{ji}(\hat{\mu}) + p_{ji'}(\hat{\mu}) &< 2m - \hat{p}_i - \hat{p}_{i'}, \\ p_{ji}(\hat{\mu}) + p_{ji'}(\hat{\mu}) &< 2m - \min(p_{i\iota}(\mu), p_{i\iota'}(\mu)) - \min(p_{i'\iota}(\mu), p_{i'\iota'}(\mu)). \end{aligned}$$

1242 As by construction $p_{i\iota}(\mu) < p_{i\iota'}(\mu)$ and $p_{i'\iota'}(\mu) < p_{i'\iota}(\mu)$ then the expression above
 1243 is equivalent to: $p_{ji}(\hat{\mu}) + p_{ji'}(\hat{\mu}) < 2m - p_{i\iota}(\mu) - p_{i'\iota'}(\mu)$. As the shortest path between
 1244 i and ι as well as between i' and ι' are unchanged from μ to $\hat{\mu}$ it follows that we can
 1245 further rewrite into:

$$p_{ji}(\hat{\mu}) + p_{ji'}(\hat{\mu}) < 2m - p_{i\iota}(\hat{\mu}) - p_{i'\iota'}(\hat{\mu})$$

1246 However, the above statement implies that in network μ that either ι or ι' has
 1247 two paths with lengths of at most m but this violates the definition of exact local
 1248 trees.

1249 We can now show that when link $\iota\iota'$ is deleted the new shortest path between i
 1250 and i' in $\hat{\mu}$ has a length of exactly $2m - \hat{p}_i - \hat{p}_{i'}$. This is shown by demonstrating there
 1251 is an agent j such that $p_{ji}(\hat{\mu}) = m - \hat{p}_i$ and $p_{ji'}(\hat{\mu}) = m - \hat{p}_{i'}$. This can be shown
 1252 follows. Suppose that $p_{ji}(\hat{\mu}) = m - \hat{p}_i$. We will demonstrate that $p_{ji'}(\hat{\mu}) = m - \hat{p}_{i'}$.
 1253 As $p_{ji}(\hat{\mu}) = m - \hat{p}_i$ it follows that $p_{j\iota}(\hat{\mu}) = m$. From the definition of exact local
 1254 trees there must exist a path of length less than m between j and ι' in network μ .
 1255 As argued in the paragraph above neither of these paths can be strictly shorter than
 1256 m and consequently they must both be exactly m .

1257 The number of shortest paths of length p which become altered for agent i is
 1258 $(\kappa - 1)^{p - \hat{p}_i - 1}$ for $p = \hat{p}_i, \dots, m - 2, m - 1$. This can be demonstrated as follows. If
 1259 agent $p_{i\iota}(\mu) = m$ and $p_{i\iota'}(\mu) = m$ then no shortest paths are altered; this is clear as
 1260 agent i as none of the unique shortest paths includes $\iota\iota'$ as they have at most length
 1261 m . If instead $p_{i\iota}(\mu) = m - 1$ then the unique shortest path from i to ι' includes $\iota\iota'$ is
 1262 the last link; this implies a new shortest path if $\iota\iota'$ is deleted. Thus if $p_{i\iota}(\mu) = m - 1$
 1263 then one shortest path of length m is lost. When $p_{i\iota}(\mu) = m - 2$ then one path of

length $m - 1$ is lost by the same argument; moreover $\kappa - 1$ paths that has $\iota\iota'$ as the second last link. By induction this can be done at higher order and thus for shorter distances. Using the number of rerouted paths shown above we can establish the total number of shortest paths in network $\hat{\mu}$ for agent i that has a length of p :

$$\#_i^p(\hat{\mu}) = \begin{cases} \kappa(\kappa - 1)^{p-1} - \mathbf{1}_{>\hat{p}_i}(p) \cdot (\kappa - 1)^{p-\hat{p}_i-1}, & p \leq m \\ (\kappa - 1)^{2m-\hat{p}_i-p}, & p \in (m, 2m - \hat{p}_i]. \end{cases} \quad (\text{B.3})$$

By combining the count of shortest paths rerouted with their new length we can generalize the loss for any agent from the deletion of link $\iota\iota'$ when all agents are homogeneous of type x :

$$u_i(\mu) - u_i(\hat{\mu}) = \sum_{l=1}^{m-\hat{p}_i} [(\kappa - 1)^{l-1} \cdot (\delta^{l-1+\hat{p}_i} - \delta^{2m-(l-1)-\hat{p}_i})] \cdot z(x, x). \quad (\text{B.4})$$

We can aggregate the losses across homogeneous agents of type x and we arrive at the following expression:

$$U(\mu) - U(\hat{\mu}) = \sum_{l=1}^m [2l \cdot (\kappa - 1)^{l-1} \cdot (\delta^{l-1} - \delta^{2m-(l-1)})] \cdot z(x, x). \quad (\text{B.5})$$

Exact local trees - gains from linking across types. We move on to establishing the gains of establishing a link in a perfectly sorted network where each component is an exact local tree.

The gains to agents ι and j of forming a link ιj are direct benefits and the new indirect connections that are accessed through the link ιj . For agent ι the benefits from forming a link with j can be computed with Equation B.3 where the input length is added one (as ιj is added to the shortest path). Recall $\check{\mu} = \mu \cup \{\iota j\} \setminus \{\iota\iota', jj'\}$.

$$u_\iota(\check{\mu}) - u_\iota(\mu) = \left[\sum_{l=0}^m (\kappa - 1)^l \cdot \delta^l + \sum_{l=0}^{m-1} (\kappa - 1)^l \cdot \delta^{2m-l} \right] \cdot z(x, \tilde{x}). \quad (\text{B.6})$$

The above expression is relevant for evaluating the pairwise gains as it captures individual benefits for a pairwise formation of a link by ι and j . However, we are also interested in the sub-connected network as it allows to assess the efficiency. Suppose instead now that ι' and j' also form a link; thus $\iota j, \iota' j'$ are formed while $\iota\iota', jj'$ are deleted. Let $\tilde{\mu} = \mu \cup \{\iota j, \iota' j'\} \setminus \{\iota\iota', jj'\}$.

1285 Let i be an agent of type x and let \hat{p}_i still denote the least distance to either ι or
 1286 ι' . We can calculate the benefits for i when $\iota j, \iota' j'$ are formed. The benefits are the
 1287 indirect connections to agents of type \tilde{x} with whom agent i has no connections in μ .
 1288 The aim is to count the number of paths of a given length.
 1289 For a given agent i' of the other type \tilde{x} it must hold that the shortest path in $\tilde{\mu}$
 1290 between i, i' either contains the link ιj or the link $\iota' j'$, and thus the distance can be
 1291 computed as follows:

$$p_{ii'}(\tilde{\mu}) = \min[p_{ij}(\tilde{\mu}) + p_{i'j}(\tilde{\mu}), p_{ij'}(\tilde{\mu}) + p_{i'j'}(\tilde{\mu})] \quad (\text{B.7})$$

1292 We further restrict the above expression. We can use that i and i' of type \tilde{x}
 1293 can be at most $2m + 1$ away from each other. This follows from the fact that
 1294 $p_{ii}(\tilde{\mu}) + p_{i'i'}(\tilde{\mu}) = 2m$ and $p_{i'j}(\tilde{\mu}) + p_{i'j'}(\tilde{\mu}) = 2m$. As $p_{ii}(\tilde{\mu}) + p_{i'i'}(\tilde{\mu}) = 2m$ and
 1295 $\iota j, \iota' j' \in \tilde{\mu}$ then it must be that $p_{ij} + p_{ij'} = 2m + 2$. These facts together entail we
 1296 can rewrite Equation B.7:

$$\begin{aligned} p_{ii'}(\tilde{\mu}) &= \min[p_{ij}(\tilde{\mu}) + p_{i'j}(\tilde{\mu}), p_{ij'}(\tilde{\mu}) + p_{i'j'}(\tilde{\mu})] \\ &= \min[p_{ij}(\tilde{\mu}) + p_{i'j}(\tilde{\mu}), 4m + 2 - p_{ij}(\tilde{\mu}) - p_{i'j}(\tilde{\mu})]. \end{aligned} \quad (\text{B.8})$$

1297 From the above expression it follows that $p_{ii'} \leq 2m + 1$ as the expression is
 1298 maximized for $p_{ij} + p_{i'j} = 2m + 1$.

1299 The number of shortest paths from i through ιj to agents of the other type \tilde{x} can
 1300 be found using Equation B.3 for agent ι adding extra distance $1 + \hat{p}_i$.²²

- 1301 • for distance $p \in \{1 + \hat{p}_i, \dots, m + 1 + \hat{p}_i\}$ there are $(\kappa - 1)^{p-1-\hat{p}_i}$ agents;
- 1302 • for distance $p \in \{m + 2 + \hat{p}_i, \dots, 2m + 1\}$ there are $(\kappa - 1)^{2m+1-(p-1-\hat{p}_i)}$.

1303 The shortest paths from i not routed through ι but instead through ι' are those
 1304 where $p + 1 + \hat{p}_i > 2m + 1$; from Equation B.8 we know the new shortest path length
 1305 is $4m + 2 - p - 1 - \hat{p}_i$. The number of shortest paths through ι' in network $\tilde{\mu}$ will be
 1306 $(\kappa - 1)^{2m+1-(p-1-\hat{p}_i)}$ and the new length $4m + 2 - p - 1 - \hat{p}_i$. These facts together
 1307 imply:

$$\#_i^p(\tilde{\mu}) - \#_i^p(\hat{\mu}) = \begin{cases} (\kappa - 1)^{p-1-\hat{p}_i}, & p \in \{\hat{p}_i + 1, \dots, m + 1 + \hat{p}_i\}, \\ (\kappa - 1)^{2m+1-p-\hat{p}_i}, & p \in \{m + \hat{p}_i + 2, \dots, 2m + 1\}, \\ (\kappa - 1)^{p+\hat{p}_i-2m-1}, & p \in \{2m + 1 - \hat{p}_i, \dots, 2m\}. \end{cases} \quad (\text{B.9})$$

²²Shortest paths from i must contain both ιj and every link in the shortest path from i to j .

1308 From the number of paths above we can derive the change in utility from when
 1309 $\iota j, \iota' j'$ are added to the network for a given agent i of type x .

$$u_i(\tilde{\mu}) - u_i(\hat{\mu}) = \left[\begin{array}{l} \sum_{l=0}^m (\kappa - 1)^l \cdot \delta^{l+\hat{p}_i} \\ + \sum_{l=\hat{p}_i}^{m-1} (\kappa - 1)^l \cdot \delta^{2m-l+\hat{p}_i} \\ + \sum_{l=0}^{\hat{p}_i-1} (\kappa - 1)^l \cdot \delta^{2m+l-\hat{p}_i} \end{array} \right] \cdot z(x, \tilde{x}). \quad (\text{B.10})$$

1310 By aggregating over all agents of type the gain in benefits by forming $\iota j, \iota' j'$ is as
 1311 follows:

$$U(\tilde{\mu}) - U(\hat{\mu}) = \sum_{p=0}^m \left(\left[\begin{array}{l} \mathbf{1}_{<m}(p) \cdot 2 \cdot (\kappa - 1)^p + \\ \mathbf{1}_{=m}(p) \cdot (n - 2 \cdot \sum_{l=1}^{m-1} (\kappa - 1)^l) \end{array} \right] \cdot \left[\begin{array}{l} \sum_{l=0}^m (\kappa - 1)^l \cdot \delta^{l+p} \\ + \sum_{l=p}^{m-1} (\kappa - 1)^l \cdot \delta^{2m-l+p} \\ + \sum_{l=0}^{p-1} (\kappa - 1)^l \cdot \delta^{2m+l-p} \end{array} \right] \right) \cdot Z(x, \tilde{x}). \quad (\text{B.11})$$

1312 *Local trees*

1313 We can use the analysis above on exact local trees to bound the gains and
 1314 losses for (non-exact) local trees. Recall that exact local trees has the property
 1315 that $\Delta\#(n, \kappa) = 0$ and for non-exact local trees $\Delta\#(n, \kappa) > 0$. Thus the difference
 1316 between exact and non-exact local trees is that for a given agent the number of
 1317 connected other agents at exactly distance m is lower for non-exact local trees.

1318 Using the analysis of exact local trees we can compute the bounds on loss of
 1319 utility for a given agent in the local when a link is deleted - this is done by reusing
 1320 Equation B.3 as follows.

1321 We can discount the number of agents initially at distance m by $\Delta\#(n, \kappa)$. More-
 1322 over, the new distance between agents i and i' after deletion of the link $\iota \iota'$ is at least
 1323 $\min(p_{ii'}, 2m - 2 - \hat{p}_i - \hat{p}_{i'})$ at most $2m - \hat{p}_i - \hat{p}_{i'}$.²³ From these two facts we can derive
 1324 the bound in loss of utility when $\iota \iota'$ is deleted. The upper bound of loss (in terms of
 1325 magnitude) is found when new shortest paths have most distance, i.e. $2m - \hat{p}_i - \hat{p}_{i'}$;
 1326 the lower bound is found when new distance is least, i.e. $\min(p_{ii'}, 2m - 2 - \hat{p}_i - \hat{p}_{i'})$:

²³The upper bound follows from the fact that for any two agents i and i' in the local tree there is still always an agent j at distances $p_{ij} = m - \hat{p}_i$ and $p_{i'j} = m - \hat{p}_{i'}$. The lower bound can be established by repeating an argument used for exact local trees. If the new distance between two agents i and i' after deletion of $\iota \iota'$ had been less than $\min(p_{ii'}(\mu), 2m - 2 - \hat{p}_i - \hat{p}_{i'})$ then the following would be true. There would be multiple shortest paths of length less than or equal to $m - 1$ between either $(\iota$ and $j)$ or $(\iota'$ and $j)$. This would violate the property of local trees that all shortest paths of length $\leq m - 1$ are unique.

$$\begin{aligned}
u_i(\mu) - u_i(\hat{\mu}) &\leq \sum_{l=1}^{m-\hat{p}_i} \left[\max(0, (\kappa-1)^{l-1} - \mathbf{1}_{=m}(l) \cdot \Delta\#(n, \kappa)) \left(\delta^{l-1+\hat{p}_i} - \delta^{2m-(l-1)-\hat{p}_i} \right) \right] \cdot z(\mathbf{B}, \mathbf{1}) \\
u_i(\mu) - u_i(\hat{\mu}) &\geq \sum_{l=1}^{\tilde{m}} \left[(\kappa-1)^{l-1} \cdot \left(\delta^{l-1+\hat{p}_i} - \delta^{2m-(l+1)-\hat{p}_i} \right) \right] \cdot z(x, x), \quad \tilde{m} = \min(m-1, m-\hat{p}_i)
\end{aligned}$$

Fact 1. If μ is perfectly sorted and consists of $|X|$ components that each constitute a local tree with $n/|X|$ agents, then for any agent i of type x where $\hat{p}_i > 0$:

$$u_i(\hat{\mu}) - u_i(\mu) > \delta^{\hat{p}_i} \cdot [u_\iota(\hat{\mu}) - u_\iota(\mu)], \quad \hat{p}_i = \min(p_{i\iota}(\hat{\mu}), p_{i\iota'}(\hat{\mu})). \quad (\text{B.14})$$

Proof. Inequality B.14 can be rewritten into: $\delta^{\hat{p}_i} \cdot [u_\iota(\mu) - u_\iota(\hat{\mu})] - [u_i(\mu) - u_i(\hat{\mu})] > 0$. This inequality is equivalent to the expression below (derived by substituting in Inequality B.13 for agent ι and Inequality B.12 for agent i):

$$\begin{aligned}
&\delta^{\hat{p}_i} \cdot \sum_{l=1}^{m-1} \left[(\kappa-1)^{l-1} \cdot \left(\delta^{l-1} - \delta^{2m-(l+1)} \right) \right] - \sum_{l=1}^{m-\hat{p}_i} \left[(\kappa-1)^{l-1} \left(\delta^{l-1+\hat{p}_i} - \delta^{2m-(l-1)-\hat{p}_i} \right) \right] > 0, \\
&\sum_{l=1}^{m-\hat{p}_i} \left[(\kappa-1)^{l-1} \cdot \left(\delta^{2m-(l+1)-\hat{p}_i} - \delta^{2m-(l+1)+\hat{p}_i} \right) \right] + \sum_{l=m-\hat{p}_i+1}^{m-1} \left[(\kappa-1)^{l-1} \left(\delta^{l-1+\hat{p}_i} - \delta^{2m-(l-1)-\hat{p}_i} \right) \right] > 0.
\end{aligned}$$

As it holds that $2m - (l+1) - \hat{p}_i < 2m - (l+1) + \hat{p}_i$ and it holds that $l-1+\hat{p}_i < 2m - (l-1) - \hat{p}_i$ (equivalent to $l < m+1 - \hat{p}_i$) the above inequality is satisfied. \square

We can also derive bounds on the gains from connecting across types for local trees. We will not do this explicitly but instead use Definition 12 on symmetric losses in local trees. This allows to express our next result:

Fact 2. For the perfectly sorted network μ which consists of $|X|$ network components which each constitute a local tree of $n/|X|$ agents that has symmetric losses then it holds that for agents i, ι of type x and $\hat{p}_i > 0$

$$u_i(\tilde{\mu}) - u_i(\hat{\mu}) \geq \delta^{\hat{p}_i} \cdot [u_\iota(\tilde{\mu}) - u_\iota(\hat{\mu})], \quad \hat{p}_i = \min(p_{i\iota}(\hat{\mu}), p_{i\iota'}(\hat{\mu})). \quad (\text{B.15})$$

Proof. It holds that $u_\iota(\tilde{\mu}) - u_\iota(\hat{\mu}) \geq u_\iota(\check{\mu}) - u_\iota(\hat{\mu})$ as $\tilde{\mu} \subseteq \check{\mu}$ (thus all shortest paths in $\tilde{\mu}$ cannot have a length that exceeds that in $\check{\mu}$). Therefore it suffices to show:

$$u_i(\tilde{\mu}) - u_i(\hat{\mu}) \geq \delta^{\hat{p}_i} \cdot [u_\iota(\tilde{\mu}) - u_\iota(\hat{\mu})]. \quad (\text{B.16})$$

As the local tree has symmetric losses it follows that $u_\iota(\tilde{\mu}) - u_\iota(\hat{\mu}) = u_{\iota'}(\tilde{\mu}) - u_{\iota'}(\hat{\mu})$; this follows from the fact that they both gain an equal number of new shortest paths

through j, j' , this follows as j, j' have same number of paths after deletion of jj' due to symmetric losses. This entails that without loss of generality we can assume that $p_{i\iota} = \hat{p}_i$ as otherwise we could substitute ι with ι' and conduct the analysis again.

For ι and some agent i' of type \tilde{x} it holds that $p_{ii'}(\tilde{\mu}) \leq p_{ii'}(\tilde{\mu}) + \hat{p}_i$. This follows as there exists a path between i, ι and ι, i' with respectively lengths $p_{ii'}(\tilde{\mu})$ and \hat{p}_i ; thus $p_{ii'}(\tilde{\mu}) \leq p_{ii'}(\tilde{\mu}) + \hat{p}_i$. This implies the following inequality must hold:

$$\sum_{x_{i'}=\tilde{x}} \delta^{p_{ii'}(\tilde{\mu})} \geq \delta^{p_{ii}(\tilde{\mu})} \cdot \sum_{x_{i'}=\tilde{x}} \delta^{p_{ii'}(\tilde{\mu})}.$$

As $u_{\iota}(\tilde{\mu}) - u_{\iota}(\hat{\mu}) = \sum_{x_i=\tilde{x}} \prod_{l=1}^{p_{ii'}(\tilde{\mu})} \delta^{r_l} \cdot z(x, \tilde{x})$ and $u_i(\tilde{\mu}) - u_i(\hat{\mu}) = \sum_{x_i=\tilde{x}} \prod_{l=1}^{p_{ii'}(\tilde{\mu})} \delta^{r_l} \cdot z(x, \tilde{x})$ it follows that Inequality B.16 holds which proves our fact. \square

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